JOURNAL OF THE AMERICAN ROCKET SOCIETY

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NUMBER 75 **SEPTEMBER-DECEMBER, 1948**

JAMES R. RANDOLPH, Editor

The JOURNAL OF THE AMERICAN ROCKET SOCIETY is devoted to the purpose of disseminating information on the development of the rocket and jet propulsion. This is accomplished by printing original technical papers on jet propulsion, data on the latest experimental developments, historical notes, patent specifications, reviews of books and current literature, and news of the Society and individual members.

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The largest supersonic ram jet engine ever flown attained a speed far into the supersonic range in its first test flight at the Naval Ordnance Test Station, Inyokern, California, Rear Admiral A. G. Noble, U.S.N., Chief of the Bureau of Ordnance, announced today. Pound for pound of engine weight, this large ram jet, popularly known as the "flying stovepipe," delivered about 25 times the power available from the best aircraft reciprocating engines. By comparison, the power developed by this simple engine was considerably in excess of the combined horsepower of the largest four-engine planes. The ram jet was designed by the Applied Physics Laboratory of Johns Hopkins and associated universities and industries. Bendix Aviation Corporation designed the fuel control system.

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DESIGN AND FABRICATION OF WELDED LIGHTWEIGHT PRESSURE VESSELS

By J. J. Chyle

Director of Welding Research, A. O. Smith Corporation, Milwaukee, Wis.

Introduction

WHERE lightweight pressure vessels are constructed by means of welding, the design should be based on factors which will permit the utilization of the maximum allowable working stresses with adequate factor of safety.

The mechanical properties of some alloys can be increased either by heat-treatment or cold working. Such increases permit higher working stresses with a reduction in weight.

Lightweight construction can also be accomplished by selection of high-strength alloys permitting high working stresses, resulting in a low weight-stress ratio.

This paper is devoted to the various factors to be considered in the design and fabrication of welded lightweight pressure vessels. The discussion is based upon the fabrication of pressure vessels by welding rather than by other processes of construction. Welding permits new designs in pressure-vessel construction which are impossible or difficult to be obtained by other processes of fabrication, such as riveting, bolting, forging, and casting.

Developments in new alloy compositions of both ferrous and nonferrous materials for greater strength and increased chemical corrosion resistance have stimulated developments of new welding processes and procedures, resulting in welds of superior mechanical and chemical properties. These welding processes have been developed during the past ten years and are now being adapted to the welding of highly stressed sections with adequate safety and security.

The fabrication of mild steel or plain-carbon steel pressure vessels since 1925 has been widely accepted, and presents no serious problems. The welding of alloy steels, however, requires greater skill and knowledge, and in some cases extensive investigations, before it can be applied on a production basis in industry. The last war stimulated a large number of investigations in the welding of high-tensile steels and special alloys to conserve materials and labor and made possible the design and fabrication of new products. This experience has given confidence in the fabrication of highly

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stressed pressure vessels by welding, and serious consideration is given today in its application in industry.

Group Classification

The design of lightweight pressure vessels can be divided into three broad groups:

1 Vessels operating at normal temperatures and high pressures
2 Vessels operating at high temperatures and high pressures
3 Vessels operating at low temperatures and high pressures

For each of these classifications consideration must be given to chemical attack by corrosion or oxidation. Pressure vessels which require chemical resistance of the material to corrosion, generally require materials of special alloy composition.

The first classification—vessels operating at normal temperatures and high pressures, that is, ranging from 0 F to approximately 150 F—are usually fabricated from materials which have high tensile strength and are classified as alloy steels. Where corrosion resistance is necessary special alloy compositions are used.

The second classification—vessels which operate at high temperatures and pressures—require special alloy compositions, either ferrous or nonferrous, which have high strength at elevated temperatures, with resistance to chemical attack. By chemical attack is meant corrosion or loss of metal by oxidation or by chemical reaction resulting in deterioration of the alloy.

The third classification—vessels operating at low temperatures and high

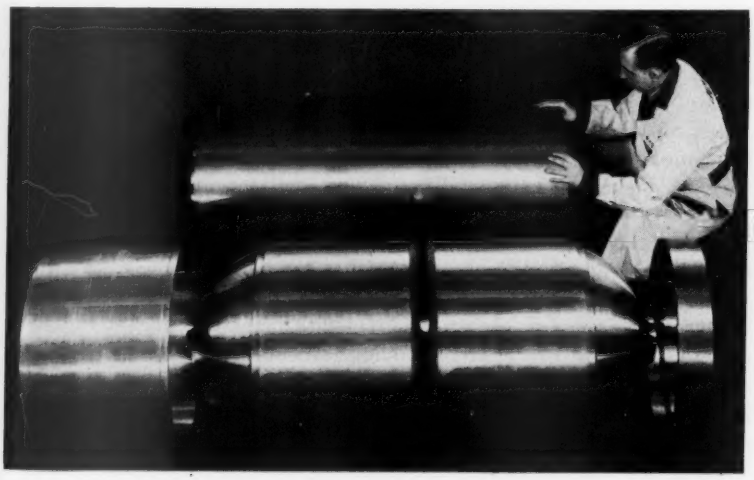

FIG. 1 AIR FLASKS WHICH WERE FABRICATED FROM HEAT-TREATED SAE 4340 V STEEL

pressures—are fabricated of special alloy compositions which have toughness at low temperatures and sufficient tensile strength for the operating pressures. Vessels which are subjected to chemical attack at low temperatures require special consideration regarding their alloy compositions.

The welding procedures which are to be used for all of these classifications will vary depending on the thickness, design, and composition of the material used. In general, the welding processes that are most commonly employed are the metal arc process, inert gas-shielded arc process, and resistance-welding process.

Design Factors

In the design of pressure vessels a number of factors must be given careful consideration before the physical design can be planned. The factors which should be considered are:

1 Selection of materials
2 The operating stresses and factor of safety
3 Stress concentration
4 Selection of welding process
5 Inspection
6 Heat-treatments

Selection of Materials

The most important factor is the selection of material which will comply with the requirements of the operating conditions. Where tensile strength only is required and temperatures are atmospheric or normal, heat-treated alloy steels can be used in the design to obtain a low weight-stress ratio. Some of the most widely used alloys for this type of service are the low-alloy steels, capable of heat-treatment, which contain alloying elements such as manganese, chromium, nickel, molybdenum, vanadium, and silicon with varying amounts of carbon. These alloys can be purchased under SAE, ASTM, ASME, and other recognized specifications.

Fig. 1 illustrates air flasks which were fabricated from heat-treated SAE 4340 steel. The alloy was heat-treated to a minimum tensile strength of 150,000 psi.

Materials of the plain carbon-steel type with increased manganese content or with small additions of other alloying elements are sometimes used after cold-working to increase their yield strength. The increased yield strength in turn permits higher working stresses and thus lowers the weight-stress ratio.

Fig. 2 shows a picture of gas-line pipes which have been cold-worked by internal sizing to increase the yield strength. The minimum yield strength

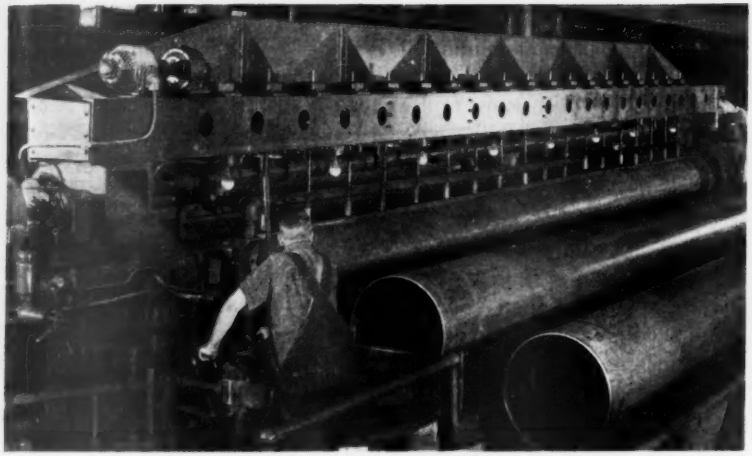

FIG. 2 PIPE SECTIONS WHICH HAVE BEEN COLD-WORKED BY INTERNAL SIZING TO INCREASE THE YIELD STRENGTH

for this pipe is 52,000 psi. The material is a plain carbon steel having approximately 0.25 per cent carbon and 1.0 per cent manganese.

The sizing operation shown in Fig. 3 increases the yield strength from approximately 41,000 psi to a minimum of 52,000 psi. Besides increasing the yield strength, the pipe is rounded to the dimension of the holding die.

For operating conditions involving corrosion attack at atmospheric or normal temperatures, special alloy materials such as the austenitic steels,

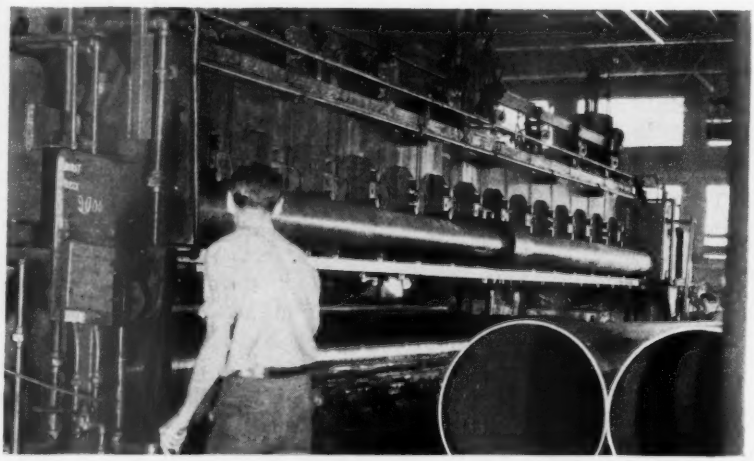

FIG. 3 EQUIPMENT USED FOR INTERNAL SIZING OF LINE PIPE

pure nickel, the nickel alloys such as Monel, Inconel, the copper-base alloys, aluminum and aluminum alloys are selected, depending upon their specific chemical resistance to the corrosive material.

For extremely low temperatures, austenitic stainless steels and nonferrous metals are generally selected such as the nickel and nickel alloys, Monel and Inconel, the copper-base alloys such as the manganese, silicon, and tin bronzes, aluminum and aluminum alloys. These metals generally have excellent ductility and strength at the low temperatures and are evaluated on the basis of impact and other types of tests at the low temperatures. Many of these materials are used for temperatures of operation ranging from minus 100 F to minus 460 F. These metals have adequate toughness combined with adequate tensile strength.

For pressure vessels which must operate at elevated temperatures, a number of alloys have been developed during the last war which are available in sheet and plate form suitable for welding. Some of these alloy compositions are modifications of the austenitic stainless steels, the nickel-chrome alloys such as Inconel, and special heat-resisting alloys containing various additions of nickel, molybdenum, cobalt, tungsten, columbium, titanium, and chromium.

In the selection of alloys for high-temperature service, consideration must be given to the creep strength as well as to the oxidation or chemical resistance for the particular temperature range at which they are to be used. These alloys are known under a variety of names and numbers and the suppliers of these alloys have data available which may be used in determining the working stresses for high-temperature service.

In the selection of materials, one of the important considerations is the cost of the material or alloy. The cost of material should always be as low as possible in order to be competitive with other materials used in the fabrication of pressure vessels. For this reason it is important to use a low weight-stress factor which will permit the most economical use of materials.

Operating Stresses and Factor of Safety

The design of lightweight pressure vessels makes it desirable to use materials which can be heat-treated or cold-worked to their optimum mechanical properties in order to base the design for maximum working stresses. The development of welding processes makes it possible now to produce alloy weld metal in the heat-treated condition with tensile strength values up to 220,000 psi. These high values are obtainable in heat-treated alloy welds of the 4–6 per cent chromium-molybdenum compositions. The operating stresses are generally based on either the yield strength or tensile strength divided by a factor of safety.

The factor of safety is governed to a great extent by the code or regulations under which the pressure vessel is fabricated. For the ASME Unfired

Pressure Vessel Code, a factor of safety from 4 to 5, based on the tensile strength of the material, is specified. In some designs the factor of safety is based on the yield strength of the material and the values for the factor of safety may be from 1.4 to 2.5, depending on the codes or regulations governing the installation. The air flask shown in Fig. 1 which operates at a pressure of 3000 psi at atmospheric temperatures, has a working stress of approximately 80,000 psi. The yield strength for the material in the heat-treated condition was established at 130,000 psi minimum. Table 1 shows the mechanical properties of heat-treated SAE 4340 (Cr-Ni-Mo) steel.

TABLE 1 TENSILE TEST RESULTS OBTAINED ON 0.505-IN. DIAMETER SPECIMENS TESTED AFTER HEAT-TREATMENT AT 1650 F OIL-QUENCH, AND TEMPERED AT 1165 F FOR 2 HR. FOLLOWED BY NORMAL AIR-COOL

Test no.	Brinell hardness	Yield strength, psi (0.01% offset)	Ultimate strength, psi	% elongation in 2 in.	% reduction of area
394-J	332	156,300	163,300	13.5	39.4
469-K	340	155,300	162,900	15.0	46.0
472-J	321	154,900	158,900	14.0	38.8
509-K	340	157,300	161,300	15.0	44.3
430-B	332	154,100	159,300	14.0	40.6
198-G	321	158,900	161,300	14.0	44.3

Line pipe which is used for the transmission of gas can be considered as a pressure vessel of long lengths. The operating pressures generally used range from 400 to 900 psi. The working stresses for some of these lines are approximately 37,400 psi, based on the yield strength of 52,000 psi minimum of the material. The line pipe is constructed according to the code for pressure piping, which allows a maximum working stress of 72 per cent of the specified minimum yield strength, for operation in rural sections. In urban locations, the maximum working stress allowed is 60 per cent of the yield strength of the material. The mechanical properties of internally sized flash-butt-welded line pipe are shown in Table 2.

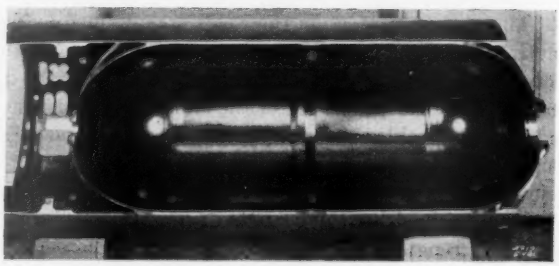

FIG. 4 CROSS-SECTIONED AIR FLASK WHICH ILLUSTRATES THE BLENDING OF UNEQUAL THICKNESSES OF MATERIAL IN ORDER TO DISTRIBUTE THE STRESSES UNIFORMLY

TABLE 2 RESULTS OF TENSILE TESTS AND CHEMICAL COMPOSITION ON FLASH-BUTT-WELDED PIPE (22-IN. O.D. × 0.344 WALL)

Test no.	Chemical analysis C	Mn	P	S	Yield point, psi	Tensile strength, psi	% Elongation in 2 in.
L-4417-L3[a]	0.28	1.10	0.012	0.032	60,000	85,000	40.5
T3	0.28	1.10	0.012	0.032	64,300	85,900	37.0
T1	0.28	1.10	0.012	0.032	....	85,800	Broke 3 in. from weld
L-4420-L3	0.23	1.05	0.010	0.024	55,600	79,500	41.0
T3	0.23	1.05	0.010	0.024	61,100	80,700	32.5
T1	0.23	1.05	0.010	0.024	....	80,800	Broke 3½ in. from weld

[a] L-3—Longitudinal tensile to direction of rolling.
T-3—Transverse tensile to direction of rolling.
T-1—Transverse tensile across flash weld.

In the design of pressure vessels it is important that all stress concentrations do not exceed the working stresses, and for this reason the design must avoid stress raisers. The flow of stresses in metals is very similar to the flow of water and all sharp corners in the design must be avoided. Abrupt changes in the joining of unequal thicknesses of material must be avoided by blending such areas to eliminate stress raisers. Where high stresses are used in a welded pressure vessel, butt joints are generally recommended. Fillet welds are usually avoided because of stress concentration at the root of the fillet welds. Fig. 4 is a cross section of an air flask and illustrates the blending of unequal thicknesses of material in order to distribute the stresses uniformly.

Generally the sections should be uniform in thickness and the welds should be of butt-type construction wherever possible. In the design the location of the welds should be placed in the least critically stressed sections. The working stresses of welds are determined in the same manner as that for the material used in the construction of the pressure vessel. These values are obtained from the weld tested in the condition that is to be used in service. The working stresses of the welds are obtained by dividing the yield strength or tensile-strength values by the same factor of safety that is used for the material of the vessel. Thus it is obvious that the data on the mechanical and chemical properties of the weld metal must be known or determined for each weld-metal composition at the operating conditions before designing the vessel. As shown in Fig. 4, the girth seam of the air-flask pressure vessel was designed on a minimum tensile strength of the weld metal of 120,000 psi in either the heat-treated or stress-relieved condition. Since the tensile strength of the material in the heat-treated condition was specified as 150,000 psi minimum, the section thickness was increased at this location to compensate for the lower tensile strength of the weld metal.

Selection of Welding Processes

A number of welding processes are available in industry today and the proper selection will depend upon the economics of the process, the type of material or alloy to be welded, and the design characteristics of the pressure vessel. The most commonly used processes are:

1 Shielded metal arc—(coated electrodes) manual operation
2 Submerged arc automatic operation
3 Inert gas-shielded arc—manual or automatic operation
4 Resistance welding—spot, seam, or flash-welding process

Other welding processes, such as atomic hydrogen, oxy-acetylene, and pressure welding, are also applicable, but their choice may depend on economic factors or on the type of material to be welded.

The metal-arc process is widely employed because of its flexibility in the use of coated electrodes, which are available in a wide variety of compositions. This welding process has wide application because it can be used to weld wide variations in plate thicknesses. The limitations of this process are governed by the availability of electrodes of special compositions and the weldability characteristics of some of the ferrous and nonferrous alloys.

In the welding of low-alloy high-tensile steels, the metal-arc process has found widespread application because special electrodes have been developed which will deposit weld metal of similar composition and mechanical properties as that of the base metal.

Tables 3 and 4 show the mechanical properties of weld metal made with Ni-Cr-Mo electrodes which were used to weld air-flask pressure vessels.

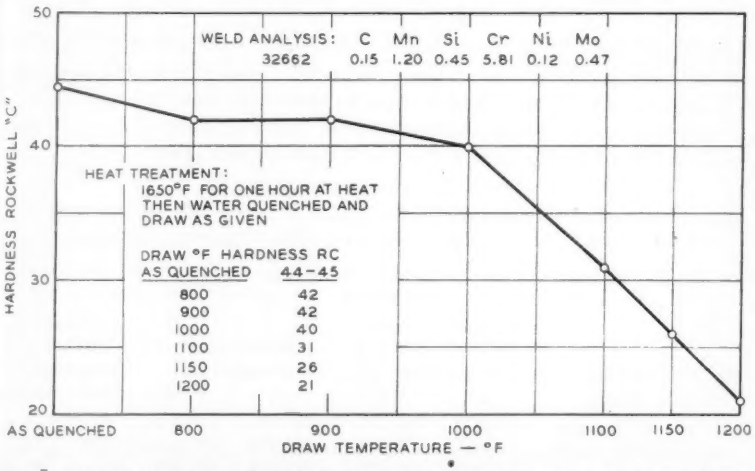

FIG. 5 EFFECT OF DRAW TEMPERATURES ON WELD HARDNESS IN THE CASE OF 4–6 PER CENT CR-MO WELD METAL

From these values it is apparent that weld metal in excess of 120,000 psi was obtained with satisfactory ductility, as shown by the elongation and reduction values. This table also shows that the weld in the stress-relieved condition has tensile strength and ductility which meet the minimum requirements for the heat-treated condition.

TABLE 3 MECHANICAL PROPERTIES OF WELDED JOINTS ON AIR FLASK MATERIAL. JOINT TENSILE TESTS ACROSS C-2 GIRTH SEAM (QUENCHED IN OIL FROM 1650 F, DRAWN AT 1175 F)

Test no.	Tensile strength, psi	% elongation (1.4 in.)	% reduction of area
884–1	130,300	13.6	46.0
2	130,000	13.6	46.0
1972–1	125,700	12.9	49.3
2	125,700	12.9	49.3
1978–1	129,500	11.4	39.2
2	128,300	10.7	35.0
8465–1	129,000	10.7	40.3
2	129,000	12.1	49.1

TABLE 4 ALL-WELD METAL TENSILE TESTS OF C-2 GIRTH SEAM

	Yield strength, psi	Ultimate strength, psi	% elongation (1.4 in.)	% reduction of area
Stress-relieved after welding at 1075 F	117,000	133,500	17.8	34.4
Heat-treated after welding, oil quench 1650 F, drawn at 1175 F	121,000	129,500	17.2	42.3

Electrodes are also available which will develop tensile strength up to a maximum of 220,000 psi after heat-treatment. These electrodes are used in alloy steels which can be heat-treated to similar mechanical properties.

Table 5 shows the tensile test results after heat-treatment of 4–6 per cent Cr-Mo weld metal, welded manually with coated electrodes.

TABLE 5 MECHANICAL PROPERTIES OF MANUALLY WELDED 4340 + V STEEL, USING 4–6 PER CENT Cr-Mo COATED ELECTRODES (HEAT-TREATED CONDITION)

Heat-treating data: 1650 F for 1 hr, quench in oil, temper at 960 F, 1000 F, 1050 F, and 1100 F.

Test no.	Tempering temp.	Average calculated tensile strength from hardness values, psi		Actual tensile strength, psi		Average Brinell hardness	
		Stock	Weld	Stock	Weld	Stock	Weld
3A	960 F, 3 hr	210,000	208,000	191,000	202,600	429	412
1A	1000 F, 3 hr	203,000	205,000	202,000	200,800	410	415
2A	1050 F, 3 hr	205,000*	164,000	193,000	151,900	415	335
4A	1100 F, 3 hr	188,000	160,000	173,800*	148,900	382	331

The effect of heat-treatment on weld metal is shown in Fig. 5 and shows the relationship between hardness and draw temperatures. Since hardness can be translated into tensile strength, it is obvious that tensile strength of approximately 220,000 psi can be obtained with certain heat-treatments.

Another application of the metal-arc process is the welding of high-temperature heat-resisting alloys which are becoming more important in present-day lightweight pressure-vessel construction.

Table 6 shows the mechanical properties of welds in $^{3}/_{16}$-in. 19-9DL plate made with $^{5}/_{32}$-in. diam. Type 19-9 Mo-W electrodes. This alloy is one of the high-temperature heat-resisting alloys, which is available in sheet form and is being used for pressure vessels.

TABLE 6 TENSILE AND BEND TESTS MADE IN BUTT JOINTS OF $^{3}/_{16}$-IN THICK 19-9DL PLATES

JOINT TENSION TESTS

Sample	Post-welding heat-treatment	Yield point, psi (by div)	Tensile strength, psi	Remarks
36522-1	Stress relieved at 1200 F 2 hr air cool	81,500	101,000	Fracture in weld
2	Stress relieved at 1200 F 2 hr air cool	85,600	102,500	Fracture in weld
36522	As-welded	113,900	134,100	Fracture in weld

BEND TESTS

Sample	Post-welding heat-treatment	% elongation in weld	Remarks
36522-Face-1	Stress relieved at 1200 F	40.5	180° bend, satisfactory
2		40.5	
36522-Root-1	Stress relieved at 1200 F	45.6	180° bend, satisfactory
2		42.8	180° bend, cracked in weld
36522-Face-1	As-welded	46.6	180° bend, satisfactory
2		45.2	180° bend, satisfactory
36522-Root-1	As-welded	53.4	180° bend, satisfactory
2	As-welded	43.4	180° bend, satisfactory

CHEMICAL ANALYSES OF 19-9DL STEEL

Plate	C	Mn	Si	Cr	Ni	Mo	Ti	Cb	W
Heat B-1236	0.31	1.05	0.55	19.03	9.35	1.21	0.21	0.53	1.12
Weld[a]	..	1.35	0.50	18.35	10.00	1.13	..	0.50	..

[a] Spectrographic determinations.

A modification of the shielded metal-arc process is the submerged-arc-welding process, which has found application in the field of alloy welding, and is limited only by the composition of the filler metal and flux that is available for the alloys to be welded. In this process, welding can be accomplished in either single heavy layers or for thick sections by multilayer deposition.

Table 7 shows the mechanical properties of weld metal deposited by the submerged-arc process in 4340 + V steel, using 4–6 per cent Cr-Mo filler wire. The weld was heat-treated by austenitizing first at 1650 F, then water quenched from 1550 F, and tempered for 6 hr at 1000 F. The tensile strength is approximately 160,000 psi with elongation of 16.5 per cent and reduction of area of 43 per cent.

TABLE 7 ALL-WELD METAL TENSILE DATA SUBMERGED ARC WELD USING 4–6 PER CENT CR-MO FILLER WIRE IN SAE 4340 + V STEEL (AUSTENITIZED, 1650 F; WATER QUENCHED, 1550 F; 6-HR TEMPERED AT 1000 F)

Ultimate strength, psi	168,000
Yield strength, psi (0.1 per cent offset)	124,000
Per cent elongation	16.5
Per cent reduction of area	43.0
Charpy impact at 32 F, ft-lb	22
Brinell hardness, BHN	
4340 + V	400
5 per cent Cr-Mo steel	363

Table 8 shows the tensile data on all-weld metal deposited by the submerged-arc process in SAE 1335 steel, using 4–6 per cent Cr-Mo filler wire after heat-treatment, consisting of a stress anneal at 1000 F and by water quenching from 1650 F and tempering at 1100 F.

TABLE 8 ALL-WELD TENSILE DATA, SUBMERGED-ARC WELD USING 4–6 PER CENT CR-MO FILLER WIRE IN SAE 1335 STEEL (STRESS-ANNEALED 4 HR AT 1000 F; WATER QUENCHED, 1650 F; TEMPERED 4 HR AT 1100 F)

	Stress-annealed at 1000 F	Tempered at 1100 F
Tensile strength, psi	143,000	147,000
Yield strength, psi (0.5 per cent offset)	124,000	131,000
Per cent elongation	12.0	9.5
Per cent reduction of area	24.0	18.5
Charpy impact, ft-lb		
Room temperature	10	12.0
−4 F	11	6
Bend tests		
Per cent elongation	18.5	20.0
Angle of bend, deg	160	70

The inert gas-shielded arc-welding process has found many applications in the light-gage field and is rapidly expanding in its use in welding a wide variety of materials. Originally this process was developed for welding magnesium and aluminum and their alloys. In this process an arc is established between a tungsten electrode and the work to be welded and is surrounded by an atmosphere of inert gas composed of either helium or argon. The process can be used either manually or it can be used in automatic

welding with or without an automatic welding head. For automatic welding-head application, the helium gas is used because it permits automatic regulation of the arc length.

This process has found application in welding materials of 0.010 in. to approximately 0.500 in. in thickness. It has also found application in the welding of heavier sections by using a large diameter tungsten electrode and high welding currents. This process is particularly suitable for the light alloys such as aluminum and magnesium, and the process requires no flux, thereby eliminating a flux-removal problem. This process can be used with either direct current or alternating current, depending on the type of metal being welded. It has also found application in welding various types of stainless steels and nickel alloys, and also low-alloy high-tensile steels such as SAE 4340. In Table 9 are shown the mechanical properties made of butt welds in 0.080-in-thick SAE 4335 sheet welded with filler wire of SAE 4340, SAE 4330, and SAE 4320 composition.

TABLE 9 MECHANICAL PROPERTIES OBTAINED IN JOINT TENSILE TESTS IN 0.080-IN. SAE 4335 SHEET WELDED WITH FILLER WIRE OF SAE 4340, SAE 4330, AND SAE 4320 COMPOSITION

Type of filler metal		Tensile strength, psi	Remarks
SAE 4340	1	160,100	Fracture in stock
	2	159,000	Fracture in stock
	3	159,500	Fracture in stock
SAE 4330	1	157,700	Fracture in stock
	2	162,500	Fracture in stock
	3	164,000	Fracture in stock
SAE 4320	1	162,100	Fracture in stock
	2	160,000	Fracture in stock
	3	157,900	Fracture in stock

The resistance-welding process has found wide application in the welding of light-gage materials, either as seam welding or flash-butt welding. This process is applicable to the welding of low-alloy high-strength steels as well as the stainless steels and the alloys used for high-temperature service.

The resistance seam-welding process is primarily used on light-gage material in which the design permits the use of two circular electrodes between two overlapping edges, to make a continuous weld. The weld is made either by a series of overlapping spot welds or by a continuous weld nugget made progressively along the joint.

Resistance flash welding is a welding process in which the entire area to be welded is heated by passage of an electric current and the weld is made by exerting pressure on the abutting edges, resulting in an upset with expulsion of metal. Fig. 6 is a photograph of a flash welder used for welding 40-ft lengths of pipe, varying in wall thicknesses from $^1/_4$ to $^1/_2$ in. This flash welder is used in the welding of line pipe, which product was described in the early part of the paper. In Table 2 are given values on joint tension tests

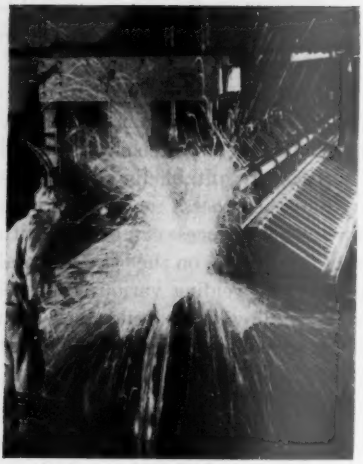

FIG. 6 FLASH WELDER DESIGNED FOR WELDING 40-FT LENGTHS OF PIPE VARYING IN WALL THICKNESS FROM $^1/_4$ TO $^1/_2$ IN.

across flash welds, in which fracture occurred in the parent metal. The flash-welding process is used in welding of low-alloy high-tensile steels, which can be heat-treated after welding to values approximating those of the parent stock. In certain designs where very high-tensile strength is required, the sections at the weld region are increased in thickness to insure a greater strength in the flash weld.

In the selection of a suitable welding process, it is important that qualification procedures be made to prove that the mechanical properties of the welds are satisfactory, that they respond to heat-treatment, and that they also have a proper chemical resistance to resist oxidation or chemical attack. The ASME Boiler Construction Code, Section IX, describes the various procedure qualifications which are required for the unfired vessel code. For welding of high-strength alloy steels and special alloy materials, special welding procedures should be qualified, depending upon the properties desired of the weld metal.

In addition to the qualification of the welding processes, it is also necessary to qualify the welding operator. Special tests for operator qualifications have been formulated by the ASME Boiler Construction Code for welding of pressure vessels. Additional tests may be required to check the skill of the operator in the welding of high-tensile alloys and special alloys used in lightweight pressure vessels. When an automatic welding process is used, it is desirable to qualify the operator for such processes.

The location of welds will depend to a certain extent on the welding process used. In all cases it should be located in the least critical area and also at such sections where accessibility for the particular welding process is most practical. In the resistance seam-welding process, it is of utmost importance that accessibility from both sides for the entire length of the seam is possible. In the metal-arc-welding process, where backup chill construction is employed, the design should provide for the removal of the backup support by either machining or grinding.

Inspection

The design of pressure vessels must be such that adequate inspection of the welds can be given. The inspection methods may consist of visual ex-

amination, radiographic, magnetic particle, fluorescent penetrant oil, supersonic, and proof testing. For some inspection processes, accessibility to both sides of the weld is necessary. In all cases it is desirable to have access to the back side of the weld in order that it can be inspected for complete penetration and soundness. These nondestructive methods of inspection are intended primarily to determine the physical soundness of the welds.

Radiographic examination has found a wide application in lightweight pressure vessels, and is considered a very reliable method of determining the soundness of the weld metal. The design of vessels must be such that full accessibility to the welds is available for complete radiographic examination.

On magnetic materials, the magnetic-particle-inspection method is used for the detection of surface and subsurface defects. It is particularly adapted for the detection of cracks near or on the surface and other discontinuities which cannot readily be observed by visual examination. A combination of radiographic examination and magnetic-particle inspection is frequently used for the determination of the soundness of the weld metal. Wherever possible, the magnetic inspection should be performed on both surfaces of the weld regions.

On nonmagnetic materials, the fluorescent penetrant-oil method is used and is a visual aid in determining surface defects. This method has found particular application in the detection of fine cracks and other discontinuities on the surfaces of nonmagnetic materials.

Supersonic methods have been developed which find application in testing of metals for the presence of discontinuities such as cracks, slag inclusions, gas pockets, and other subsurface defects. This method of inspection is not limited to magnetic materials but can be used on all types of alloys, and in recent developments in this field its range has been increased to include the inspection of light-gage materials.

Proof Testing

Proof testing is specified in some cases to check the design and to insure that the yield strength has not been exceeded when subjected to the proof-test pressure. This test is usually applied where close tolerances are necessary and the adequacy of the design and fabrication is checked. In proof testing, the pressure is applied until the stresses in the section are equal to

FIG. 7 EQUIPMENT USED TO PROOF-TEST WELDED AIR FLASKS

the minimum yield strength for the material at 0.01 per cent offset, to determine whether deformation has occurred. Measurements are taken before and after the proof-testing pressure is applied to determine the extent of any permanent deformation. The proof testing of the air flask consisted of a hydrostatic test to $1^1/_2$ times its working pressure. Fig. 7 shows the proof-testing equipment. After the test was made dilation measurements established any yielding of the material. The specification allowed a maximum of only 0.003 in. on 22 in. diameter and 0.005 in. over a straight length of 70 in.

Heat-Treatments

Consideration in the design of pressure vessels must be given to the problem of heat-treating when required in the fabrication. In the fabrication of lightweight low-alloy high-tensile pressure vessels, the parts may be heat-treated prior to welding, while in others the heat-treating operation is carried out after all welding is completed. Where distortion is likely to be encountered, special fixtures must be provided to maintain the proper dimensions. In some cases, design changes must be incorporated to minimize the effect of distortion and warpage during heat-treatment. When heat-treatment is necessary, it is also important that notch effects and stress raisers are eliminated to prevent cracking in the heat-treating operations. Where the parts are heat-treated prior to welding, it is necessary to stress-relieve the welds in order to eliminate high-residual welding stresses and to impart greater ductility to the welded joint.

It is recommended that stress-relieving or heat-treatment be given to all welded lightweight pressure vessels fabricated from low-alloy high-tensile steels. For some applications where very light sections are used and where the materials are of a nonferrous composition, stress-relieving may not be necessary. The necessity for stress-relieving must be ascertained by adequate tests.

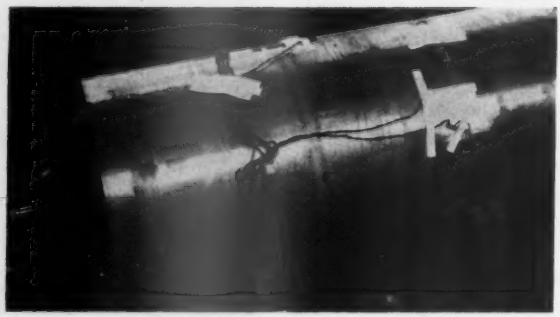

FIG. 8 AIR FLASK ON WHICH STRAIN GAGES HAVE BEEN ATTACHED TO DETERMINE THE STRESSES AT VARIOUS PRESSURES

FLASK	BURST PRESSURE	WALL THICKNESS	BURST HOOP STRESS	ACTUAL ULTIMATE STRENGTH	PER CENT HOOP STRESS OVER ACTUAL U.T.S.
9	6450	0.366	198,000	171,000	15.8
11	6675	0.377	198,500	171,000	16.0
259	5075	0.361	158,000	128,800	22.8
371	5850	0.370	178,000	152,300	16.9
2931	5850	0.376	175,000	149,900	16.8
2648	6200	0.365	191,000	162,700	17.4
1972	6320	0.379	187,000	156,300	19.8

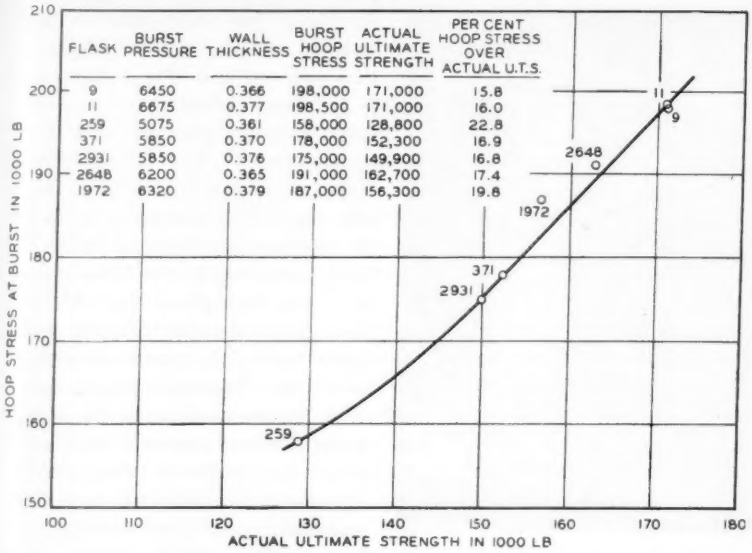

FIG. 9 RELATIONSHIP BETWEEN HOOP STRESS AT BURST PRESSURE AND ACTUAL TENSILE STRENGTH OF FLASK

Qualification of Product

For pressure vessels that are used in critical service, full-size burst tests are usually conducted to determine whether the pressure vessel meets the requirements of the calculated design. Stress measurements are taken to determine the yield and tensile stresses of the pressure vessel. Fig. 8 shows an air flask which has strain gages attached to various parts of the vessel to

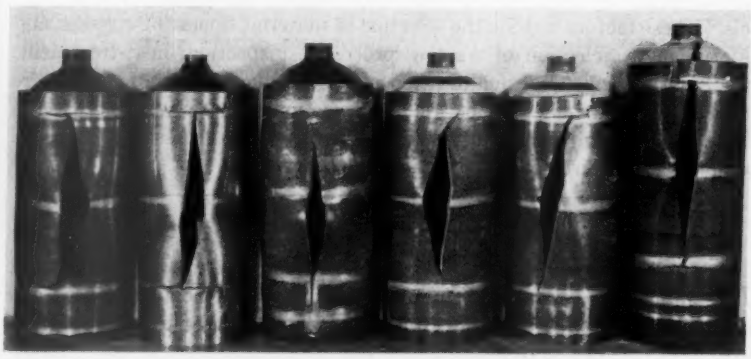

FIG. 10 RUPTURED VESSELS SHOWING PATH OF RUPTURE

FIG. 11 AIR FLASK UNDER 3000-PSI PRESSURE BEFORE DROP OF 150 FEET INTO QUARRY

determine the magnitude of the stresses at the various pressures that were applied. Fig. 9 shows the hoop stress at burst pressure for seven pressure vessels which were burst-tested. The burst hoop stresses varied from 158,000 to 198,500 psi. The variation in hoop stresses was due to modifications in heat-treatments to develop a range of tensile strengths. Fig. 10 is a photograph of a number of burst air flasks showing the nature of the path of rupture. The burst tests also give other information regarding vessel design, and the effect of attachments which may influence the over-all strength of the vessel by stress concentration at localized sections.

In addition to burst tests, other destructive tests to determine the suitability of the product may also be made. These may consist of drop tests, as shown in Fig. 11, and other special tests, depending on the service requirements. This photograph shows a view of the air flask under 3000-lb pressure, just before dropping it in a quarry from a height of 150 ft, as shown in Fig. 12.

Summary

A number of factors have been discussed which should be given consideration in the design and fabrication of welded lightweight pressure vessels. These factors include the selection of material, operating stresses, and safety factor, selection of welding processes, inspection, heat-treatment, proof testing, and final qualification of the product. These factors were used in the design and fabrication of a large number of pressure vessels in the author's plant and resulted in products which successfully complied with all the requirements for the intended service.

ARS Junior Award

AN AWARD consisting of a medal and certificate is to be presented annually by the American Rocket Society to a member of the Society, 25 years of age or under, for the best paper submitted during the year. Papers for consideration for the award must be at ARS Headquarters not later than Sept. 15, 1949. Members are urged to compete.

THE DESIGN OF TANKS FOR LIQUID-PROPELLANT ROCKET POWER PLANTS

By C. C. Ross[1] and R. B. Young[2]

Introduction

THIS paper will consider the function of tanks in rocket power plants, the operating requirements of the tanks, and the various configurations encountered in conventional rocket power plants. The designer of tanks for rocket power plants is faced with several problems foreign to conventional pressure-vessel practice which make his work difficult and exacting. It is the purpose of this paper to examine these problems and the solutions current or future, in so far as security restrictions permit. As the discussion is unclassified, it is necessary to omit certain pertinent information and data, particularly that referring to actual power plants and vehicles.

The propellant consumption of a rocket engine is very high in comparison with that of a reciprocating engine. A 2000-lb thrust engine (2000-hp at 375 mph) consumes approximately 10 lb of propellant per sec against 0.33 lb per sec for a 2000-hp aircraft engine. As a result, the bulk of propellants carried in a rocket-powered missile or aircraft represents the major portion of the initial gross weight, varying according to the design from 60 to 75 per cent. Consequently, the vehicle becomes, in a sense, a "flying tank," and the design and construction of the tanks affect the performance of the vehicle to a great extent.

The two principal types of liquid-propellant rocket engines, pump-feed and pressure-feed, require entirely different tank systems. The former, wherein the propellant injection pressures are developed by pumps, can use lightweight tanks designed to operate at low pressures, usually 50 psi or less, and in some instances can be made in contour shapes to fit particular inboard profiles. Tanks of this type represent only a small percentage of the vehicle's gross weight, consequently are not as critical in so far as design requirements as the second type described below. In the latter type, the propellant feed pressures are derived from gas pressure, the gas source being either inert gas stored at high pressure or a chemical reaction producing gaseous products at the required pressure.

The tanks of the pressure-feed engine therefore must stand high pressures, sometimes at greater than ambient temperatures or at extremely low temperatures. The working pressures involved dictate a spherical or

[1] Member ARS, Jun. ASME, Chief Designer, Aerojet Engineering Corporation, Azusa, Calif.

[2] Member ARS, Senior Design Engineer, Aerojet Engineering Corporation, Azusa, Calif.

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cylindrical configuration to keep the weight within reason. In a typical pressurized rocket engine, the tanks comprise approximately 20 per cent of the total gross weight and 75 per cent of the dry weight of the engine. The above figures show clearly why the design and the fabrication of this class of tanks have received so much attention in the rocket industry. Since the tanks also enclose the bulk of the volume of any rocket-powered vehicle, it is obvious that it is most efficient to make use of the tanks as structural members. In general, this can be done only in the case of a pressurized engine, and in many instances the tanks themselves form both the structure and the skin of the vehicle, carrying all thrust and air loads.

With the above in mind, the general requirements of rocket-engine tanks are discussed in the order of relative importance.

1 *Lightweight:* Above all, tanks must be of minimum weight. It can be shown that the range of a given vehicle is a function of the mass ratio, ζ, which is the propellant weight divided by the initial or take-off weight. In maintaining this parameter at the maximum possible value, the ratio of propellant weight to tank weight must be kept at a maximum.

2 *Operability:* If rocket-powered vehicles are to be used in quantity, they must be easily serviced, handled, and stored; and malfunctions resulting from tank or tank-component failures must be kept at an absolute minimum. Rocket-engine tanks must meet this requirement, and the designer must be cognizant of all the problems related to such tanks before attempting a specific design.

3 *Low Cost:* Rocket-powered vehicles are costly articles. The tanks, however, are relatively simple when compared with the guidance, control, and propulsive equipment. It follows that considerable thought and effort should be expended toward the evaluation of low-cost designs in which items 1 and 2 are not compromised.

4 *Smooth Contours and Alignment:* As mentioned above, tanks are often the outer skin structures of a rocket-powered vehicle, requiring smooth surfaces and contours to minimize aerodynamic drag. Also, as the thrust and air loads are frequently transmitted through the tank shells, alignment of the several tanks is necessary if consistent flight characteristics are to be maintained. It should be noted that these requirements are peculiar to rocket-engine tanks, excluding possibly droppable gas tanks for aircraft as related to drag considerations.

5 *Corrosion Resistance:* While corrosion resistance is not a general requirement, it is important because of the nature of many rocket propellants. Many rocket-tank designs have been compromised because of the corrosion problem. In some applications a satisfactory solution to this problem in itself insures the success of the particular design.

Classification of Rocket Power Plant Tanks

Tanks for rocket power plants can be divided into two principal categories: Storage gas flasks, and propellant tanks. The gas flask is for the purpose of storing the feed gas at high pressure. This feed gas is used to force the propellants into the combustion chamber, or in the case of pumping systems, to pre-pressurize the propellants to prevent cavitation at the pump inlets. During the cycle of operation of the power plant, the pressure in the flask will vary from a maximum to a nominal value slightly above the operating pressure of the propellant tanks. The maximum or design pressure of the gas flask is usually between 2000 and 5000 psi. It can be shown that flasks of spherical design, storing a given weight of gas, are equal in weight regardless of pressure, provided similar materials and working stresses are assumed. Thus an important factor in establishing maximum pressure is often space requirements as it follows that higher initial pressure will result in a design of smaller space requirements. In actual practice, however, a very decisive factor in establishing maximum pressure is the means available for compressing the gas. Compressor equipment up to 2000 psi is readily available, up to 3000 psi is somewhat rare, and up to 5000 psi is considered special equipment.

The gases used for nearly all applications are noncorrosive, being air, nitrogen, or helium. Helium is used only when the margin of weight saved is justified by its additional expense over air or nitrogen.

As previously stated, propellant tanks are divided into two distinct classes, those used in conjunction with pressurized systems and those used with pump-fed systems. These types of tanks are hereafter referred to as Class I and Class II, respectively, and along with other design features and characteristics, are shown in Table 1.

TABLE 1 CLASSIFICATION OF PRESSURE-VESSEL REQUIREMENTS FOR CONVENTIONAL ROCKET POWER PLANTS

Description	Operating Pressure Range (psig)	Remarks
Fuel tanks:		
Class I	400–600	
Class II	0–50	
Oxidizer tanks:		
Class I	400–600	Corrosion resistance required
Class II	0–50	Corrosion resistance required
Gas flasks:		
Class I	2000–5000	

The tank operating pressures of conventional engines using Class I tanks usually vary, depending on the specific design, from 400 to 600 psi, and the

Class II tanks from 0 to 50 psi. Although some calculations show that higher pressures would be more desirable for Class I, such claims have not been substantiated by actual experiment to the writers' knowledge.

The establishment of operating pressure for the Class II vessels is determined by the suction characteristics of the propellant pumps. In general, it may be stated that the higher range of pressure is required for higher-thrust engines and for higher pump-operating speeds. In the usual case, the design of the Class II propellant tank is not a problem of the pressure involved, but rather one of fabrication difficulties on minimum gages, or of stability considerations.

Effect of Propellant Fluids

The oxidizers used in conventional rocket engines are nitric acid, hydrogen peroxide, and liquid oxygen. Resistance to corrosion is the prime problem of vessels for nitric acid; noncatalytic properties are required of materials used with hydrogen peroxide; and good low-temperature properties are necessary for the materials used with oxygen. Although these material-property requirements are different for the three common oxidizers, it will be seen that choice of specific materials is limited to a very few, some of which can be used for all applications.

Fuels are not critical, as a general rule, in so far as tank material is concerned. Conventional fuels are alcohols, hydrocarbons, and various amines, which are noncorrosive. Most common fuels, however, possess the property of being good solvents. This must be considered in the design of gaskets and other appurtenances using plastic materials.

Configurations and Mechanical Features of Rocket Power Plant Tanks

From a designer's standpoint, the mechanical features of specific tank designs are of interest. The configurations used for Class II tanks in pump-feed engines are usually of one general type, namely, cylindrical with dished ends, separate from the vehicle structure. The operating requirements dictate that the operating pressures be safely withstood, that no structural loads be carried, and that inertia loads be absorbed. Because of low thickness-to-diameter ratio (1/500), such tanks are extremely sensitive to external pressure, and usually provisions must be made to prevent the application of external differential during the service cycle.

Several tank configurations in use today are worthy of note. A brief discussion of the more important configurations follows:

1 *Integral Designs:* In the general case, the three tanks (pressure, oxidizer, and fuel) are welded together as one assembly. Adjoining tanks have common ends, and the tank shells form the external skin of the vehicle. The order in which the tanks are arranged is not mandatory but is usually dic-

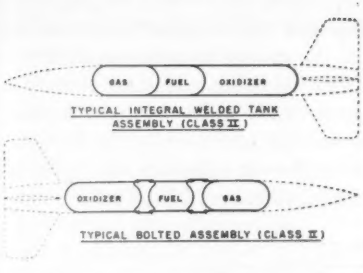

FIG. 1 CLASS II ROCKET POWER PLANT TANK CONFIGURATIONS

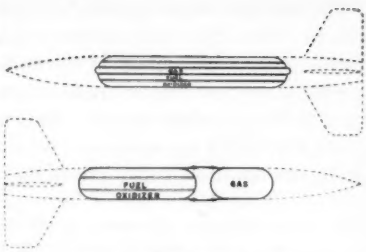

FIG. 2 CONCENTRIC TANK CONFIGURATIONS

tated by stability requirements. For instance, if stability in free flight is a requirement, it is customary to locate the heavier pressure tank forward so that the empty center of gravity will be at the maximum forward position. Fig. 1 shows a typical configuration.

In some installations it is undesirable from a design standpoint to weld the tanks as an assembly, and bolted connections are used to join the tanks or connecting structures. In the case of airborne controlled vehicles, space and center-of-gravity limitations often dictate that the tanks be physically separated. In these cases, the tanks still form part of the vehicle body but are connected by structure. Such an arrangement is also shown in Fig. 1.

Another integral configuration includes concentric tanks as a welded assembly. The propellant tanks may be annular with the pressure tank in the center, or may be concentric to each other with the pressure tank separate. Both types are shown in Fig. 2. In some specific applications this configuration has merit, but, in general, it results in a greater dry weight since a greater amount of material is required to contain a given volume.

2 *Separate Designs:* As previously discussed, Class II tanks for pump-feed engines have low pressure requirements and are of relatively large volume. Hence it is advantageous to construct them as separate units rather than integral with the vehicle body. The tanks are designed to carry on external loads and are of minimum weight and construction. Because of the low working pressures, it is sometimes possible to fit the tanks to the vehicle contours without incurring a weight penalty. The German V-2 propellant tanks are typical examples. The oxygen tank in the V-2 had a total volume of 168 cu ft and weighed only 268 lbs.

In airborne piloted vehicles, space limitations sometimes preclude the use of conventional (spherical or cylindrical) pressure vessels. In these instances the pressure tank may consist of a small-diameter tube wound around the propellant tanks. (See Fig. 3.) As the surface of such a configuration is poor from an aerodynamic standpoint, such tanks are usually installed as separate units within the vehicle skin. This configuration sometimes has weight advantages since high-strength seamless tubing is readily available in small diameters.

The gas-flask requirements for a pump-feed type of power plant are not critical. Since the total volume of gas at the storage pressure required represents a small percentage of the vehicle's total volume, clusters of more or less standard lightweight pressure cylinders can be utilized with little effect upon the total empty weight. This method was also used by the Germans in the V-2, which incorporated two clusters of seven cylinders, each cylinder having a volume of 1.35 cu ft and a working pressure of 3000 psi.

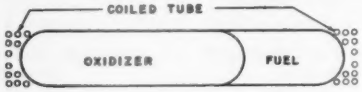

FIG. 3 TUBULAR GAS FLASK DESIGN

As the gas flask of pressure-feed engines may account for approximately 40 per cent of the dry engine weight, a spherical configuration is advantageous, although in the general case, diameter and pressure limitations necessitate the use of a somewhat modified design, taking the form of hemispherical ends separated by a short cylindrical section.

Some applications utilizing tanks of 12-in. diam or less incorporate gas flasks with concave hemispherical heads for simplification of assembly and installation. Other applications utilize several pressure tanks with high length-to-diameter ratio arranged as protective and load-carrying structure around the lighter, less rigid propellant tanks. Any such modified design will result in a corresponding increase in weight as the length-to-diameter ratio of the vessel increases so long as the working stresses are held constant.

The Class I propellant tanks of the pressure-feed engine are generally cylindrical with elliptical ends. Some installations incorporate concave ends, sacrificing some weight in the interest of ease of assembly and installation.

Materials of Rocket Power Plant Tanks

The materials phase of the rocket power plant tank problem is critical. Stringent weight requirements dictate the use of materials of high physical properties, and the equally stringent alignment and contour requirements limit the degree of heat-treatment after assembly. The large physical size of the tanks also makes adequate and uniform heat-treated properties very difficult to obtain. Finally, due to the expendable nature of most rocket power plants and the projected need for large numbers, great emphasis must be placed upon the use, whenever possible, of noncritical materials. This latter condition notwithstanding, the various materials, critical and otherwise, in use today will be discussed in so far as security permits.

In considering any storage-gas-feed engine, it can be said that its success depends upon a satisfactory gas flask. The bulk of the difficulties encountered in building tanks for rocket power plants stem from this item. In

selecting a material, the factors mentioned in the preceding paragraph receive prime consideration.

The heat-treatable alloy steels such as AISI-4130 are very good on paper. Working stresses up to 125,000 psi are possible, and the material is widely used. However, extreme difficulty is commonly experienced in the welding and heat-treatment of large-size tanks (diam = 754 in.) of 4130 steel. Uniform welding and heat-treatment are difficult to obtain, and resulting failures on proof test are common. The fact that all welding must be done before heat-treatment further complicates the fabrication and assembly, and warpage during heat-treatment is often cause for rejection if the alignment tolerances are exceeded. In the case of heat-treated steel tanks having threaded bosses finish-machined prior to installation, difficulty is encountered in protecting machined surfaces and maintaining thread sizes to gage following heat-treatment. The use of stainless bosses alleviates this problem to some extent, although such a solution is not entirely satisfactory.

The heat-treatable (martensitic) corrosion-resistant or semicorrosion-resistant steels such as AISI types 410 and 501 sometimes are used. These materials have the advantage of superior scaling resistance but require expert welding techniques and accurate heat-treat control if satisfactory results are to be obtained. Pertinent physical properties are given in Tables 2 and 3. High cost relative to X4130 and 410 is a disadvantage.

TABLE 2 THE PHYSICAL PROPERTIES OF X4130 STEEL

Source	AN-QQ-5-585		ANC-5		
Condition	Normalized or otherwise heat-treated (N)		Normalized		
Properties	For thickness up to 0.188″	For thickness up to 0.188″	Bar, plate, tubing over 0.188″ thick	Heat-treated to Ftu = 125,000 psi	Heat-treated to Ftu = 150,000 psi
Tensile strength Ftu (psi)	95,000	90,000	90,000	125,000	150,000
Yield strength Fty (psi)	75,000	70,000	70,000	100,000	135,000
Elongation in 2 inches, per cent	15 (max.)	18 (min.)	....	24	20
Hardness	.....	.....	....	....	....
Density (lb/in.^{3})	.....	.....	0.2833	0.2833	0.2833
Young's modulus E (psi)	.....	.....	29 $\times 10^6$	29 $\times 10^6$	29 $\times 10^6$
Shear modulus G (psi)	.....	.....	11 $\times 10^6$	11 $\times 10^6$	11 $\times 10^6$
Poisson's ratio	.....	.....	0.30	0.30	0.30
Shear strength Fsu (psi)	.....	.....	55,000	75,000	90,000

TABLE 3 THE PHYSICAL PROPERTIES OF STAINLESS-STEEL TYPES 19-9, 501, 410

Type	19-9		501	410	
Source	Universal Cyclops		Rezistal Crucible Steel Co.	Rezistal Crucible Steel Co.	
Conditions	Stress relieved at 1200 F after cold work	Annealed at 1800 F	Annealed at 1550 F	Annealed	Heat-treated
Properties					
Tensile strength Ftu (psi)	130,000	100,000	60–80,000	65–75,000	100–185,000
Yield strength Fty (psi)	90,000	50,000	25–30,000	35–40,000	60–170,000
Elongation in 2 inches, per cent	23	23	30–40	25–35	10–30
Hardness	30–35 "C" Rock	90–95 "B" Rock	160 Brinell	150 Brinell 80 "B" Rock	180–375 Brinell
Density (lb/in.^{3})	0.286	0.286	0.279	0.280	0.280
Young's modulus E (psi)	29.5×10^6	29.5×10^6	29×10^6	29×10^6	29×10^6
Shear modulus Shear modulus G (psi)	.....	.....	.....	.....	.....
Poisson's ratio	0.291	0.291	.....	.....	.....

The austenitic stainless steels are only fairly satisfactory for use in pressure tanks. They have the advantage of being capable of use in the as-welded condition but with attendant low working stresses. The common 18–8 types (302, 321, and 347) are not available in the work-hardened condition in gages above 0.063 in., hence must be used in the annealed condition. The alloy, Uniloy 19-9DL (Universal Cyclops), possesses superior physical properties relative to the common 18–8 types in the annealed condition, that is, yield strength of 50,000 to 60,000 psi against 30,000 to 35,000 psi and utimate strength of 110,000 psi against 80,000 psi. Moreover, Uniloy 19-9DL is available in the so-called "hot-cold worked condition" in gages up to $\frac{1}{2}$ in. In this condition, the yield strength is from 90,000 to 105,000 psi with a corresponding ultimate strength of 130,000 to 140,000 psi. Weldability is excellent as the material is fully stabilized. Uniloy 19-9DL may be used in the as-welded condition with good strength of welds. This alloy has the disadvantage of high cost (approximately 70 cents per lb) and of containing a fair percentage of chromium, making it a critical material. Also, it is widely used in turbojet engines for turbine blades, hubs, combustors, and tail pipes, all of which make its availability for quantity use in rocket engine tanks in time of emergency doubtful. Pertinent physical data are given in Table 3.

The common aluminum alloys are being used more widely in rocket engine pressure tanks as fabrication techniques improve. The weldable alloy, 61ST, has desirable properties. Welding and heat-treatment of this alloy are critical, although consistent results can be obtained with proper control. Among the nonweldable types, 75ST is the most widely used. This alloy is classed among those of the highest physical properties of any of the aluminum alloys, the ultimate strength being of the order of 80,000 psi. In tank applications, 75ST extruded tubing with bolted or otherwise mechanically fastened heads must be used. Pertinent physical data of these and other aluminum alloys are given in Table 4.

TABLE 4 THE PHYSICAL PROPERTIES OF 61ST AND 75ST ALUMINUM ALLOY SHEET

Type	61ST	75ST	
Source	ANC-5	ANC-5	
Conditions	All sizes	Thickness 0.016 to 0.039 in.	Thickness 0.040 to 0.249 in.
Properties			
Tensile strength Ftu (psi)	42,000	70,000	72,000
Yield strength Fty (psi)	35,000	60,000	62,000
Elongation in 2 inches, per cent	8	7	8
Hardness, 500 Kg. Brinell	95	150	150
Density (lb/in.^{3})	0.098	0.10	0.10
Young's modulus E (psi)	10×10^6	10.4×10^6	10.4×10^6
Shear modulus G (psi)	3.8×10^6	3.8×10^6	3.8×10^6
Poisson's ratio	0.33	0.33	0.33

Relative to materials for fuel tanks, it can be said that any of the materials discussed are entirely suitable. Also, other steel and aluminum alloys are sometimes used, as the weight limitations are not so severe for the fuel tank since it is usually a small percentage of the engine empty weight. Magnesium is suitable for use with most fuels, and lightweight tanks can be obtained if proper welding and heat-treatment techniques for particular designs are developed.

In selecting materials for oxidizer tanks, consideration must be given to corrosion resistance. This requirement eliminates the carbon-alloy steels and magnesium unless special protection for exposed surfaces is provided. The austenitic stainless steels are the most widely used corrosion-resistant materials. The common 18–8 types are virtually eliminated for use in oxi-

dizer tanks because of their low physical properties. The alloy, 19-9DL, exhibits relatively high physical properties as well as good corrosion resistance, which is a rare combination of properties in steel. This material is being widely used at this time in oxidizer tanks of various rocket engines.

The common aluminum alloys all have adequate corrosion resistance for use in oxidizer tanks. The principal problem in the use of these alloys is providing adequate protection from galvanic action and atmospheric corrosion. Oxidizer tanks of 14ST, 61ST, and 75ST are in use today, giving satisfactory service.

Protecting the surface of materials that are not corrosion-resistant from the action of strong oxidizers is a singular solution to the oxidizer tank problem. Plastic coatings or bags of sufficient resistance to the oxidizers to permit the unlimited fully loaded storage of tanks so protected are visualized, and workable designs appear to be practicable. Development is still in the experimental stage and several plastics appear favorable. The use of aluminum or stainless clad materials is also considered, although fabrication techniques of such materials are not sufficiently developed for practical use.

Assuming that materials for the various types of tanks must be selected from the materials discussed in the preceding section or from similar areas, working limits must be established in order to determine the most efficient design. Confining the discussion to Class I or high-pressure configurations, factors affecting the detail design will be discussed.

All rocket power plant tanks must be loaded with their respective fluids either at the place of manufacture, a fueling location, or the actual scene of operation. The tanks must incorporate provisions for this servicing which will facilitate the attendant operations. This means a fill boss or connection of adequate size must be provided and located so that bleeding of the tanks may be accomplished readily through the one opening. Fill bosses should be designed with the thought that in some instances tanks will require emptying in the case of an emergency. Provisions are necessary for controlling the liquid level in propellant tanks so that adequate expansion volume is automatically left after servicing. If the vehicle is a recoverable type of a particular classification, some means of venting the residual pressure upon recovery must be provided. The pressure tank should have some means of venting pressure easily and readily, regardless of application. To facilitate hydrostatic testing and cleaning, some pressure tanks incorporate an opening of adequate size to allow the tank to be drained easily of liquid and visually inspected.

Some applications of liquid rocket-powered vehicles require that the vehicles be capable of being stored for long periods over rather extreme temperature ranges when loaded with propellants. If either of the propellants is corrosive, the elevated storage-temperature requirement (160 F) is quite severe, as the rate of corrosion of materials, in general, increases rapidly with temperature.

To relieve excessive pressures which might be built up by the thermal expansion of the propellants during storage, special relief valves must be incorporated in the tanks. This is also true for peroxide tanks, where any pressures due to slow decomposition must be adequately relieved.

Tanks of materials that are not corrosion-resistant must be suitably protected both inside and outside for protracted storage. The oils used in commercial applications are not applicable in the case of air flasks. One means of internal protection is to store the flask filled with an inert gas such as nitrogen at low pressure. Rust on the inside of an air flask not only decreases the operating safety factor but can cause malfunction of the rocket engine by clogging vital orifices further downstream.

The designer must consider the handling to which a particular tank is to be subjected prior to its use, and provide accordingly. Procedures for handling large-size tanks from pump-feed power plants are quite elaborate because of their extreme lack of stability and rigidity. Concentrated loads must be avoided by provision of adequate pickups, and damaging external differential pressures must be guarded against.

If the tanks are to be handled loaded, extreme caution must be exercised in the design to insure against leaks or damage from inertia pressures caused by moderately rough handling. An example of this consideration is the integral welded design wherein the two propellant tanks are separated by an essentially unstressed diaphragm. The diaphragm could be deformed or otherwise damaged by inertia pressure resulting from rough handling, with fire or explosion the result in the case of hypergolic propellants. Obviously, tanks should have all openings suitably closed during handling even though empty. Thought should be given to cleaning requirements in all tanks. In the case of peroxide tanks, it is absolutely imperative that all foreign material be removed and the tank's inside kept clean. The V-2 propellant tanks incorporated large manholes to facilitate cleaning and inspection.

Besides carrying the pressure, flight, and thrust loads during flight, the tank system of a rocket power plant must perform its part of the function of supplying the propellants to the rocket motor continuously at the proper pressures. This means that the pressure gas, if used, must be introduced so as not to plunge through the propellant or cause excessive foaming. Usually, in gas-feed engines, the pressure gas is brought into the tank above the normal liquid level, and its kinetic energy is dissipated by baffles and deflectors which allow no direct impingement upon the liquid. If a chemically pressurized system is used, the hot pressurizing gas line is often brought in at the bottom of the tank and terminated at the top so that a significant amount of cooling is obtained. For applications involving only axial forward acceleration, tank outlets need only be equipped with antivortex baffles to prevent formation of a free vortex during the final seconds of operation.

In many rocket-powered vehicles, accelerations of varying magnitudes in the six directions are encountered. The problem of maintaining uninterrupted flow from the propellant tanks during the entire operating period under these accelerations complicates the basic tank design to a great extent. Several methods of insuring continuous flow have been put into practice in this country. Five such methods are shown schematically in Figs. 4 and 5: the external bag, internal bag, diaphragm, piston, and swinging pipe. The sketches are self-explanatory, and it is only necessary to add that each method has its advantages and disadvantages. The authors favor either the piston or the diaphragm as the installation of both is simple, and the servicing not complicated to any degree. The bag installations have difficulties related to bleeding during propellant filling and bag failures resulting from excessive wrinkling in the loaded condition. The swinging pipe, as shown, is not suitable for extreme fore-and-aft accelerations, and has the disadvantage of the packed joint.

The design of tanks for rocket power plants presents various problems, the solutions of which, as of this date, are only partial. In the opinion of the authors, future developmental work is required on heat-treatment, welding, corrosion protection of noncritical alloys, improved production design for reduced cost, and operational features.

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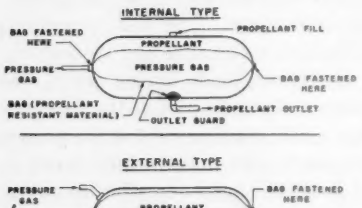
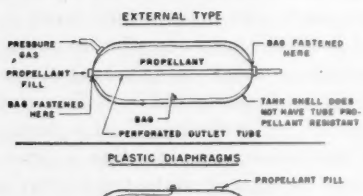




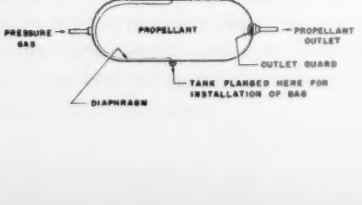
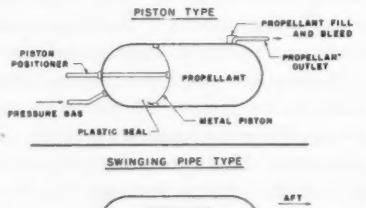


FIG 4 (LEFT) PLASTIC BAG METHODS OF EFFECTING CONTINUOUS FLOW



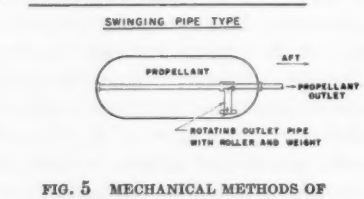


FIG. 5 MECHANICAL METHODS OF EFFECTING CONTINUOUS FLOW

TANK PRESSURE FROM COMBUSTION CHAMBER

Edward F. Chandler

Mem. ASME, Consulting Engineer, Chandler Research Corporation, Brooklyn, N. Y., Mem. ARS

THE simplest form of liquid-fuel jet engine for high-speed short-range missiles is the so-called one-shot system, in which the fuel and propellant are contained in tanks capable of standing the combustion-chamber pressure, and are forced into the combustion chamber by the pressure on an inert gas. Compactness and lightness are essential features of its design, and in certain uses quick starting and reliability are also essential.

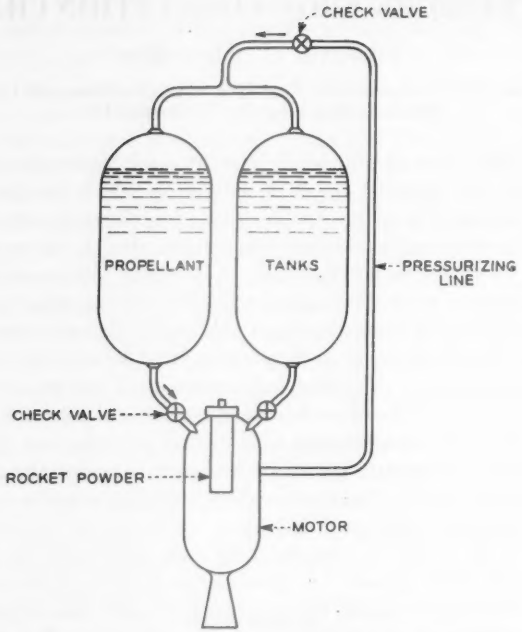
The employment of a separate inert gas from a high-pressure tank adds weight and complications to such a rocket, and lessens its reliability in uses requiring storage. The tank must contain an amount of gas which when expanded to combustion-chamber pressure will fill both propellant tanks. It must be strong enough to hold that pressure in a substantially smaller volume. Regulator valves are necessary to reduce the gas pressure to the pressure needed. The whole system is subject to leaks, and may not be in working order when needed.

Another consideration in the design of such missiles is the speed with which they can be launched. At present this depends on the method employed for initially energizing the propulsion jet, and this in turn depends largely upon the kind of combustible agents employed. But whether the agents used are self-igniting when admitted to the combustion chamber, or are such as must be ignited by special means, there still is an appreciable time which must pass before the motor develops its full thrust. It is desirable to reduce this time lag as much as possible.

Room for Improvement

In examining the lines along which possibilities for improvement may lie, at least two fields appear to warrant exploration. In place of the heavy and bulky pressure-storage tank, it may be practical to generate the gas under pressure at the required rate by means of a slow-burning powder. For a comparatively short flight the powder charge in cartridge form would be small. For a longer flight a plurality of cartridges could be used. Fired in series they would give a reasonably constant pressure. Firing may be automatically controlled by pressure or temperature changes in the combustion chamber. This system would reduce the weight and bulk of the rocket by eliminating the pressure tank.

Starting lag can be reduced by monopropellants or by self-igniting propellant combinations, but these introduce certain hazards in handling and in operating which to a degree militate against their potential advantages. Some interesting research is being done along this line.



LIQUID-FUEL JET ENGINE WITH POWDER IGNITION CHARGE SHOWING METHOD OF PRESSURIZING FUEL TANKS FROM COMBUSTION CHAMBER

A better plan, at least with propellants now available, seems to be the use of a fairly large charge of rocket-propellant powder within the combustion chamber. This charge is large enough to build up the full working pressure before the supply of the liquid propellants starts. It can be made to generate enough heat to ignite the propellants as they come in, so that the rocket gets off to a quick start, as a powder rocket does, yet has the superior efficiency of liquid fuels for the greater part of its run.

Pressurizing From Combustion Chamber

The writer's improvement on these ideas for which patent application is now on file, is shown in Fig. 1. It uses a powder-igniting charge, as described above, and then uses pressure from the combustion chamber to enable the propellants to flow in from the tanks. As these tanks are above the combustion chamber, and the whole apparatus is being accelerated, this pressure is all that is necessary to get the liquids to flow into the combustion chamber. The volume of gas bled from the combustion chamber for this purpose approximately equals the volume of the liquids,

so no great difficulty will be involved in cooling it to a temperature the pipes can stand. A safety valve in this pipe can readily prevent excessive pressures anywhere in the system.

As the differential pressures between the tanks and the combustion chamber are small, the valves for regulating the flow of propellants can be of fairly large dimensions, and easy to make and adjust with the required degree of accuracy.

It would also be possible to use two or more tanks for each propellant, pressurizing one while the other filled from a much larger unpressurized tank. The latter arrangement will be particularly desirable when we get around to building space ships, for after their initial blastoff to five miles per second the acceleration of these space ships will be small, although their mass ratios will be enormous. A simple and dependable supply system is desired, together with very light disposable fuel containers.

Elimination of the storage of gas under high pressure will be advantageous here, as well as in military applications, and so will elimination of the pumps which are characteristic of rockets with unpressurized tanks, such as the V-2.

Jet Propulsion in Commercial Air Transport

IN THE field of military air transportation speed trends have been continually upward, and recent flights of new Air Force high-speed jet bombers have caused much speculation as to the future of jet-propelled aircraft. In commercial air transportation the goal of the air lines in satisfying the public demand has been, and always will be, increased speed, especially if at the same time improvements in safety, comfort, reliability, and economy result. Can jet propulsion, which has so revolutionized military aviation, be applied to advantage in civil air transportation?

To evaluate this problem a number of generalized studies are set up to show the effect of airplane, engine, and performance variables. A careful analysis of variables, such as availability of engine types, fuel requirements, take-off and climb performance, block-to-block speed, comfort, direct and indirect operating costs, profitable operating ranges, and desirable airplane size, leads to a prediction of future trends in civil air transportation.

It is concluded that the adoption for commercial use of 30-passenger turbojet transports, operating at 35,000 ft at cruising speeds of 500 mph for nonstop ranges of 250 to 1000 miles, can be both technically feasible and commercially profitable for 1951. This type of transportation will offer to the commercial air passenger more speed, greater flight frequency, and more comfort at fares comparable to present standards. The airline operator will be offered a single-type transport that will efficiently service over 80 per cent of the domestic air business. (Abstract of an article by Robert E. Page, *Aeronautical Engineering Review*, August, 1948.)

FIVE-POUND THRUST LIQUID MONOPROPELLANT ROCKET

By Manuel C. Sanz

North American Aviation, Inc., Los Angeles, Calif.

THE rocket described in this article was test fired on June 13, 1948, at a site in the Mojave Desert, Calif. With a weight of less than one pound at take-off, it attained an altitude of several thousand feet as determined by its vapor trail. The aluminum-alloy rocket, 16 in. long and $1^1/_4$ in. in diam, was not recovered although several hours were spent in searching the desert sagebrush.

The construction of the rocket was undertaken as an outside hobby by engineers in the Aerophysics Laboratory of the North American Aviation, Inc., Los Angeles, Calif.

It was desirable to keep the construction simple and inexpensive, and for this reason thought was given to the possible use of a liquid monopropellant. Since concentrated hydrogen peroxide is now available in the United States, this chemical was given first consideration.

FIG. 1 FIVE-POUND THRUST MONOPROPELLANT TEST ROCKET

Hydrogen peroxide is not too hazardous to handle if certain precautions recommended by the manufacturer are observed, and in spite of its low specific impulse (146 sec for 100 per cent H_2O_2), its high average density, low combustion-chamber temperature (1360 F for 90 per cent) and monofuel character more than make up for the low specific impulse.

Hydrogen peroxide may be decomposed exothermically by a number of catalytic agents.

Power for the propellants pumps of the German V-2 (A-4 German designation) was obtained from the decomposition of highly concentrated hydrogen peroxide by the use of a concentrated solution of either calcium or potassium permanganate. In the German ME-163 rocket airplane, permanganate impregnated ceramic pellets were used for the same purpose. In this case the propellants used were hydrogen peroxide and hydrazine hydrate.

Several metals have also been found catalytically to decompose hydrogen peroxide. The solid catalyst used in this rocket was a specially impregnated window-wire screen. Eight of these screens, cut to a diameter of approximately one inch, were used in this rocket.

Pressurizing of the hydrogen-peroxide tank was accomplished by using a small carbon-dioxide bulb (these are readily available in the drugstores). Water-flow tests showed that a pressure of 830 psi down to 350 psi could be

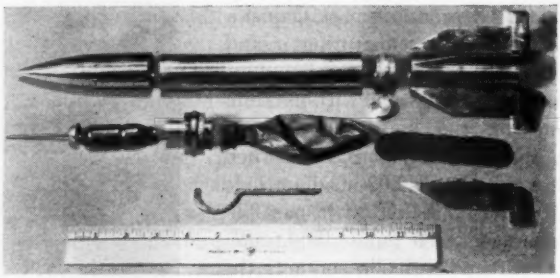


FIG. 2 SMALL TEST ROCKET SHOWING COMPONENT PARTS

obtained while discharging the carbon dioxide over a period of eight sec while ejecting 100 cc of water through a 0.02-in. diam orifice.

The motor was designed with a $^1/_8$-in. diam throat for an average chamber pressure of 400 psi and a propellant flow rate that would develop 5 lb of thrust. The thrust was confirmed experimentally on static tests.

The launching was assisted by making use of a $^1/_4$-in. airplane shock cord stretched over a pulley on top of the 15-ft launching tower.

Description. Fig. 1 shows the assembled rocket. Fig. 2 shows an exploded view of its component parts. The balloon shown in this figure was not used in the actual launching since the missile was fired vertically. However, the balloon was used in horizontally fired static tests. The balloon is attached so that the carbon dioxide inflates it, pressurizing the hydrogen-peroxide tank. Fig. 3 is a schematic drawing illustrating the

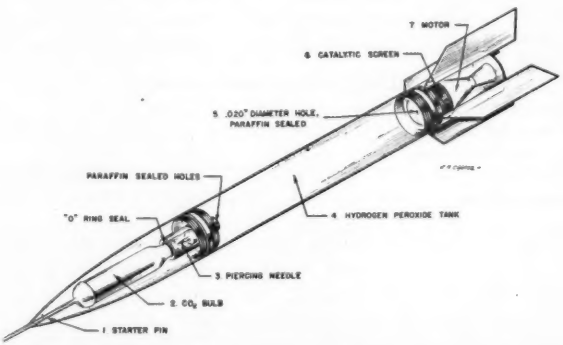


FIG. 3 SCHEMATIC DIAGRAM FIVE-POUND THRUST MONOPROPELLANT TEST ROCKET

various component parts. The rocket is started by applying a hammerlike blow on the starter pin (*1*). (This is done automatically in the launching tower.) The blow forces the CO_2 container (*2*) against a sharp steel needle (*3*), puncturing it and releasing the carbon dioxide through four small holes, previously sealed with paraffin, for pressurizing the hydrogen peroxide tank (*4*); the hydrogen peroxide is then forced through a small 0.02-in. diam hole (*5*) also previously sealed with paraffin. The paraffin acts as a burst diaphragm. When the hydrogen peroxide contacts the catalytic screen (*6*) in the motor (*7*), it is decomposed exothermically. The thermal decomposition of the peroxide provides the thrust.

FIG. 4 PLACING ROCKET IN LAUNCHING TOWER PRIOR TO LAUNCHING

Pressurizing with carbon dioxide has certain advantages over compressed air, mainly in that CO_2 is liquid at room temperature and 830 psig and thus offers a greater volume of gas without increase in weight of the container than would be required for higher pressures if compressed air were used. The danger in using CO_2 is that the critical temperature is low, 31 C (87.8 F).

Rocket Characteristics.

Weight, empty	273 g
Weight of fuel	148 g
Weight, full	421 g
Length	16 in.
Diameter	1¼ in.
Thrust, measured	5 lb
Time of firing	8 sec
Calculated altitude, vertical trajectory in vacuum at cutoff	6700 ft
Maximum altitude	40,800 ft
Velocity at cutoff	1475 ft per sec
Probable values with drag	
Cutoff velocity	1000 to 1200 ft per sec
Maximum altitude	20,000 ft

Launching. A 15-ft launching tower was constructed using two 2 in. angle irons (Fig. 4). The tower was erected and inclined at an angle approximately 5 deg from the vertical. Two wires running the full length of the tower and attached to the tower at top and bottom were used as guides for a tubular container which was used as a receptacle for the rocket. A ¼-in. diam airplane-shock cord was stretched from the ground over a pulley

on top of the tower and attached to the receptacle held by a removable pin at the bottom of the tower. The rocket, filled with hydrogen peroxide, was placed in the receptacle, Fig. 4, and it was launched by pulling a cord which released the lock pin holding the receptacle and rocket against the tension of the shock cord. Halfway up the tower the nose hit a protruding arm which was spring-loaded, starting the rocket on its powered flight. This arm was automatically pulled away from the rocket after causing the puncturing of the carbon-dioxide bulb. Trial launching without fuel ejected the rocket about 30 ft off the ground.

In the powered launching, the missile was fired into the wind and the time of powered flight was measured to be about $8^1/_2$ sec (duration of the vapor trail) at which time the missile was lost from sight. The altitude at cutoff was determined by simple triangulation by two observers, and was approximated to be 6000 ft.

Future Plans

It is planned to build a larger missile using the same fuel and construction principles. A larger size will permit a gain in mass-weight ratio that was not possible on the small rocket which had threaded fittings. One rocket has been considered weighing approximately one pound empty, capable of carrying about $3^1/_2$ lb of hydrogen peroxide and being 30 in. in length and $2^1/_2$ in. in diam.

If made out of suitable materials and with provisions for venting through a slit rubber cap which would be closed off at the time of firing, the peroxide can be stored indefinitely in the rocket.

In the larger type rocket it is planned to use an air-pressurizing system.

Additional thrust could be gained and still maintain design simplicity by adding some combustible solid fuel in the motor. This could be in the form of a charcoal or wooden liner, or still, by using paraffin or heavy grease which would be combustible when the temperature of decomposition of the hydrogen peroxide reached the ignition temperature of the material. As far as it is known, hydrogen peroxide has not been used as an oxidizer for solid fuel.

Uses

An outstanding feature of this rocket is that it permits a great deal of flexibility in making physical changes for the purpose of experimentation. These changes may be made economically in various models due to the simplicity of the rocket's construction.

Several possible applications for uses other than as a projectile have been suggested: Aerodynamic studies (because of the rocket's flexibility of changing its physical characteristics); underwater studies; test rocket for monopropellants; and gas generator for other than rocket uses.

INFLUENCE OF EARTH'S GRAVITATION ON THE REQUIREMENTS OF THE VERTICAL TRAJECTORY ROCKET WITH SPECIAL REFERENCE TO ESCAPE

By John Paul Sellers, Jr.

Research Associate, Ohio State University, Columbus, Ohio, Mem. ARS

The problem of reaching extreme altitudes is basically one of overcoming the earth's gravitation. Therefore, when the earth's gravitation is analyzed with respect to its influence on a rocket-propelled vehicle in a vertical trajectory, a theoretical analysis of the problem of reaching extreme altitudes is readily obtained. Since such an analysis is not new, the first portion of the paper is a review of the fundamental dynamic considerations of the problem. The review includes showing how the effect of earth's gravity on the requirement of the long-range rockets can be evaluated by the concept of a gravitational velocity, or a minimum velocity that must be attained by the rocket to achieve its objective. An ideal rocket for minimum expenditure of energy would leave the earth with a speed equal to the gravitational velocity and coast to its objective.

The paper considers the principal differences between the ideal and actual long-range rockets, inasmuch as it accounts for the additional energy required of the actual rocket due to the time for acceleration of such a rocket to a gravitational velocity of escape. It also accounts for the variation of earth's gravitational attraction upon the rocket overpowered as well as coasting flight. As a result of these considerations a table of correction factors is given which can be used with the ideal rocket equations to give approximate actual rocket results.

Nomenclature

a = acceleration of rocket at any instant, ft per sec^2
$\bar{a}$ = average acceleration over powered flight, ft per sec^2
β = gravity ratio, $\bar{g}/g_o$
c = effective exhaust velocity of rocket motor, fps
$\bar{c}$ = average effective exhaust velocity over powered flight, fps
D = drag due to air resistance, lb
E = energy, ft-lb per unit mass
F = force, lb, and thrust, lb
g = acceleration of gravity at any point in space, ft per sec^2
g_o = acceleration of gravity at earth's surface, ft per sec^2
$\bar{g}$ = average value of acceleration of gravity over powered flight, ft per sec^2
h_p = altitude obtained by rocket at the end of powered flight, ft
K = gravitational constant
m = instantaneous mass of rocket during powered flight
M = mass of rocket system exclusive of the propellants

M_p = mass of propellants in rocket at beginning of flight
M_o = initial gross mass of rocket = $M + M_p$
ν = acceleration factor = $\bar{a}/g_o$
P = a point in space and the distance to a point P in space
R = radius of the earth, ft = $21 \cdot 10^6$
s = distance, ft
t = time, sec
t_p = duration of powered flight, sec
v = velocity of rocket at any time, fps
V_{max} = maximum velocity; velocity of the rocket at end of powered flight, fps = V_P
V_{P_o} = gravitational velocity. The velocity acquired by a body when it reaches the earth's surface if dropped from a point P in space, fps
V_P = gravitational velocity between a point P and another point which is located at the distance h_p from the surface of the earth, fps = V_{max}
V_{e_o} = gravitational escape velocity at the surface of the earth = 36,700 fps
V_e = gravitational escape velocity at the distance h_p above the earth's surface, fps

Introduction

IF IT had been man's fate to be born on a planet of a mass much less than our earth's, say about the size of Mercury or even Mars, the first escape journey would in all probability by now be history. The rocket, as the most promising means of propulsion for the escape journey at the present time, first and uppermost, must overcome the attraction that matter has for other matter—an attraction of sufficient intensity to keep even the unruliest of our explorers confined to the earth.

The external retarding forces (see Fig. 1) which the rocket must overcome to be liberated from the earth are: The gravitational attraction of the earth; and the aerodynamic resistance of the earth's atmospheric cover. The fundamental concepts necessary for an introduction to the problem of escape from the earth by rocket-jet propulsion can be ascertained from a study of the gravitational attraction of the earth. The effect of the atmosphere on the rocket flight can be, and has been, theoretically analyzed, (1—6)[1] but it is outside the scope of this paper and will be neglected henceforth in the discussion. Indeed, the question quite logically may be asked, "Cannot the atmosphere be ne-

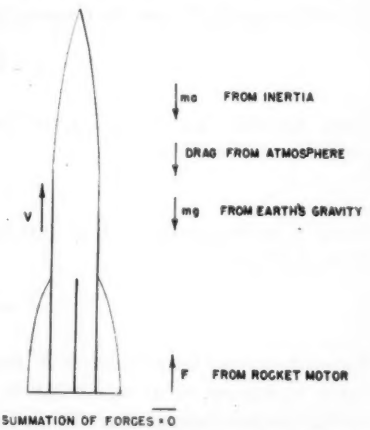


FIG. 1 FORCES ACTING ON A ROCKET IN VERTICAL FLIGHT THROUGH THE ATMOSPHERE

[1] Numbers in parentheses refer to references listed at end of paper.

glected, since it comprises such a small portion of the total distance which must be traveled in the escape journey?" Theoretical considerations (2) give an affirmative answer to such a question.

It is interesting to recall at the outset of a discussion dealing with gravity that although gravitation is as old as matter, there have been only two significant contributions to its explanation. Newton, by enunciating the Law of Universal Gravitation, which we shall soon apply to the escape rocket flight, made a useful contribution to the study of its effect, and apparently Einstein's theory of relativity (7) has now shed a faint beam of intellectual light on the scientific mystery of what is gravity. Unfortunately, there is only one method known at present to overcome the influence of gravity on an object and that is simply, but crudely, exert a greater and opposite force on the object (8).

Minimum Energy Required to Escape From the Earth

The Law of Universal Gravitation as stated in most textbooks of physics is: Each particle of matter attracts every other particle with a force F which is directly proportional to the product of their masses and inversely proportional to the square of the distance between them.

Hence the force F is given by the inverse square law

$$F = K\frac{m_1 m_2}{s^2}$$

where K is the proportionality factor commonly referred to as the gravitation constant.

Now if m_2 represents the mass of the earth and s is made equal to the radius of the earth R, then the force on m_1 at sea-level is

$$F_o = K\frac{m_1 m_2}{R^2} \quad \ldots\ldots [1]$$

From Newton's law of motion, the force exerted by the earth on a mass m_1 at the earth's sea-level is

$$F_o = m_1 g_o \quad \ldots\ldots [2]$$

where g_o is the acceleration of gravity at sea-level. Combining Equations [1] and [2] gives

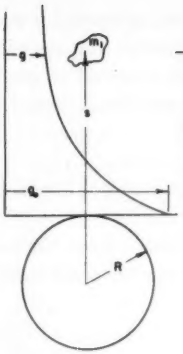
$$K = \frac{g_o R^2}{m_2}$$

Substituting the latter value of K into Equation [1], the attraction F of the earth on a mass m_1 at any point on a radial path from the center of the earth outward through space is, accordingly,

$$F = m_1 g_o \left(\frac{R}{s}\right)^2$$

where s is the distance from the point under observation to the center of the earth. It follows from Newton's law of motion, $F = ma$, and the law of universal gravitation that if m_1 be taken as unity the variable force F is not only the force of gravity at some point in space, but it is also the acceleration of gravity g on a unit mass located at that point. (See Fig. 2.) Hence

$$g = g_o \left(\frac{R}{s}\right)^2 \quad \ldots\ldots\ldots [3]$$



PLANET	g_o FT. PER SEC.^{2}
MERCURY	8.7
VENUS	27.6
EARTH	32.2
MARS	12.2
JUPITER	84.8
SATURN	37.5
URANUS	35.9
NEPTUNE	35.9
MOON	5.2

FIG. 2 A PLANET'S GRAVITATIONAL FIELD

Fig. 3 is a graphical representation of Equation [3] divided by g_o. It is seen that g/g_o is asymptotic to the axis of abscissas, which implies that the gravitational attraction of the earth extends to infinity and can never be entirely escaped. However, Fig. 3 also shows that the gravitational attraction at approximately 4000 miles from the earth's surface is only 25 per cent of its sea-level value. Therefore, at a finite distance from the earth the influence of the earth's gravity on the escape rocket will become so small that the attraction of some other heavenly body will predominate. As a first approximation, however, the effect of the mass of the moon, sun, and other planets can be neglected. The escape rocket is then assumed to travel to infinity to escape from the earth.

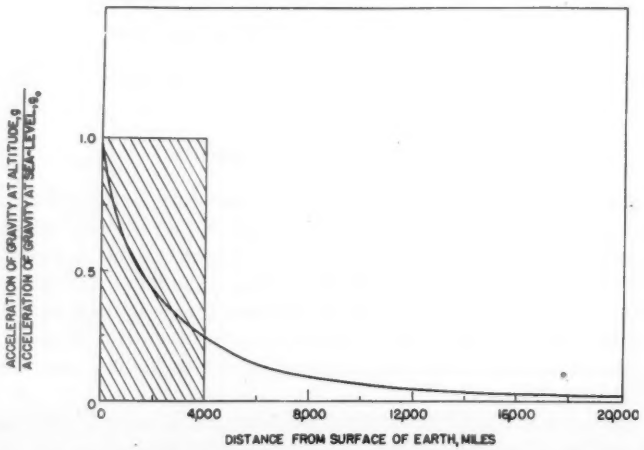


FIG. 3 RATIO OF ACCELERATION OF GRAVITY AT ALTITUDE TO SEA LEVEL

By definition, work or energy is equal to the product of a force and a distance so the area under the curve of Fig. 3 represents energy per unit mass. The energy E required to move a slug mass[2] from s_1 to s_2 against the retarding force of gravity is found by integrating Equation [3] between these limits:

$$E = g_o \int_{s_1}^{s_2} \left(\frac{R}{s}\right)^2 ds$$

In the problem of escape from the earth's gravitational influence, assuming the starting location is the earth's sea-level,

$$s_1 = R$$

$$s_2 = \infty$$

Hence the energy per unit mass required to escape from the earth is given by

$$E = g_o \int_R^\infty \left(\frac{R}{s}\right)^2 ds = g_o R^2 \int_R^\infty \frac{ds}{s^2}$$

or

$$E = g_o R \qquad [4]$$

The above result states that the minimum energy required to liberate a mass of one slug from the attraction of the earth, or for that matter any planet, is equivalent to moving a unit mass a distance equal to the radius of the planet under a constant force equal to the acceleration of gravity at the planet's surface. (See the cross-hatched area of Fig. 3.) Substituting in Equation [4] the numerical values, 32.2 ft per sec^2 and 21×10^6 ft for g_o and R gives

$$E = 32.2 \times 21 \cdot 10^6 = 6.79 \cdot 10^8 \text{ ft-lb per unit mass}$$

The above is the minimum energy required to liberate a unit mass from the planet earth.

The Gravitational Velocity

Neglecting the possibility of nonvertical trajectory escape-rocket flights to take advantage of the rotation of the earth, for a rocket to escape from the earth, that is, overcome earth's gravitation, or to achieve a given altitude with the minimum expenditure of energy, the flight path should obviously be vertical. The deceleration process is then a natural one, that is, the rocket coasts to zero velocity as it approaches the point in space where the attraction of some other heavenly body on the rocket is greater than the attraction of the earth.

It follows from the principle of the conservation of energy, neglecting the

[2] Slug mass and unit mass are used interchangeably in the paper.

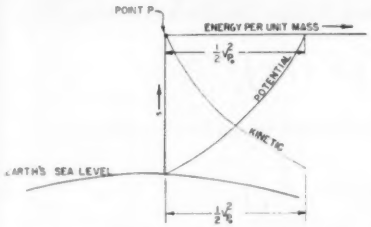


FIG. 4 CONSERVATION OF ENERGY APPLIED TO A FREELY FALLING BODY

energy lost in overcoming air resistance, that the sum of the kinetic (energy of motion) and potential (energy of position) energies of a body freely falling into space is constant. (See Fig. 4.) If a body originally at rest at a certain point P in space falls to the earth, its velocity when it strikes the earth is denoted by V_{P_o}, then its kinetic energy per unit mass when it strikes the earth will be $^1/_2V_{P_o}^2$. Conversely, if a body leaves the earth with the velocity V_{P_o}, which will be called the gravitational velocity, it will coast to the point P, due to the kinetic energy becoming transformed to an equal amount of potential energy for the motionless body at the point P. The potential energy at P is therefore equal to the energy expended in overcoming gravity to reach P. Thus

$$\frac{1}{2}V_{P_o}^2 = \int_R^{R+P} g\,ds$$

where P now represents the distance from the surface of the earth to the

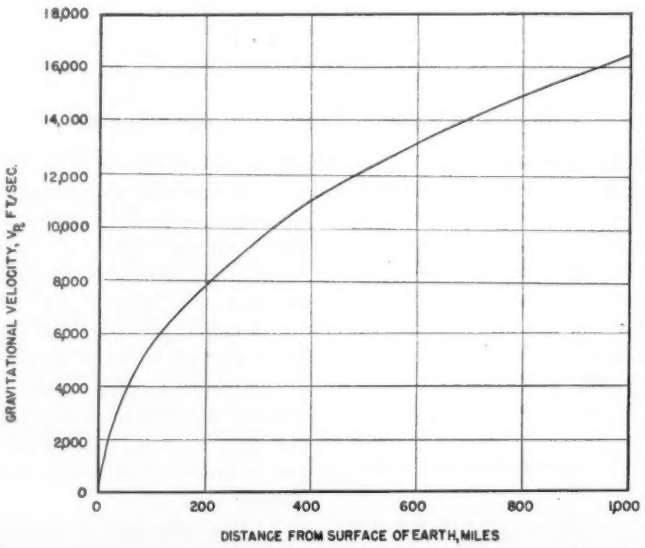


FIG. 5 THE VERTICAL OR GRAVITATIONAL VELOCITY CORRESPONDING TO THE ENERGY REQUIRED TO COAST A GIVEN DISTANCE (0–1000 MILES) FROM THE EARTH'S SURFACE

point P in space. Substituting Equation [3] into the latter equation gives

$$\frac{1}{2} V_{P_o}^2 = g_o \int_R^{R+P} \left(\frac{R}{s}\right)^2 ds = g_o R^2 \int_R^{R+P} \frac{ds}{s^2}$$

Hence the gravitational velocity with reference to sea level is given by

$$V_{P_o} = \sqrt{2g_o R\left(1 - \frac{R}{R+P}\right)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [5]$$

From the latter equation, the gravitational velocity which, once again, is the velocity for a body to leave the earth in order to coast to the height P, can be easily calculated. Fig. 5 presents values of V_{P_o} as a function of the distance P from the earth's surface.

By substitution of $P = \infty$ and $R = 21 \cdot 10^6$ ft (radius of the earth) into Equation [5], it is found that the gravitational velocity of escape, denoted by V_{e_o}, from the earth's sea level is about 7 miles per sec or 36,700 ft per sec. Since the escape velocity V_{e_o} is a constant which appears frequently in the literature, and will be used below, it is important that there is no misconception regarding its meaning. It is the minimum velocity that a body must attain at the earth's sea level if it is to escape from the earth's gravitational attraction with the minimum expenditure of energy.

The gravitational velocity of escape at any distance s from the surface of the earth, denoted by V_e, is

$$V_e = R\sqrt{\frac{2g_o}{R+s}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [6]$$

Maximum Velocity From Minimum Energy

The actual rocket vehicle being initially at rest on the earth must be accelerated to the required gravitational velocity and will, in the time for acceleration (commonly referred to as the burning time or powered flight), traverse a given distance, denoted as h_p. (See Fig. 6.) Hence the required gravitational or minimum velocity to coast to the point P will not be the gravitational velocity V_{P_o} which corresponds to a fall from P to the earth's sea level, but a lower velocity which will be designated V_P.

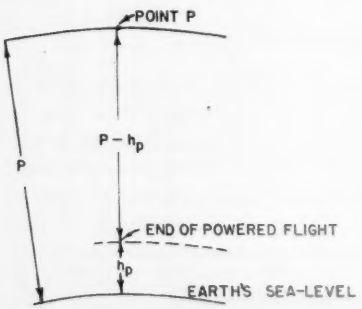


FIG. 6 NOMENCLATURE FOR THE VERTICAL TRAJECTORY ROCKET

At this point in the discussion, a change in the terminology is in order. Although the recently in-

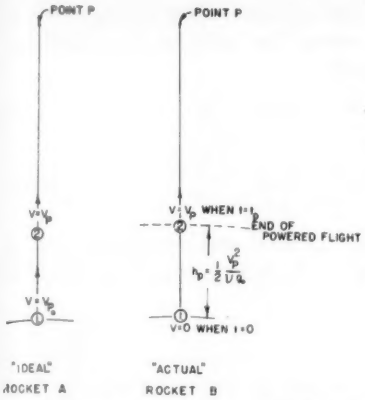


FIG. 7 IDEAL AND ACTUAL ROCKET TRAJECTORIES

troduced gravitational velocity V_P is the minimum velocity necessary for the rocket to coast the remaining distance after burning to P, $P - h_p$, for a minimum energy analysis of the rocket flight, it is also the maximum velocity that the rocket must obtain and henceforth will be denoted V_{max}. An equation will now be derived for V_P or V_{max}.

The numerical difference between V_{P_0} and $V_P = V_{max}$ depends on the ratio of the burning-time distance h_p to the total distance from the earth's sea level to the point P. In the following analysis the distance h_p will be related to the velocity V_P by introducing an acceleration parameter ν. Let ν equal the average acceleration of the rocket during the burning time distance h_p, divided by g_o. Hence

$$\bar{a} = \nu g_o \quad [7]$$

and then from elementary physics

$$h_p = \frac{1}{2}\frac{V_P^2}{g_o \nu} = \frac{1}{2}\frac{V_{max}^2}{g_o \nu} \quad [8]$$

Fig. 7 represents the path of two rockets, A and B, leaving the earth for the point P in space. Suppose that rocket A represents the ideal from the standpoint of energy required. With this supposition, according to the above theoretical results, it must leave the earth with the gravitational velocity V_{P_0} and its kinetic energy per unit mass at launching, $\frac{1}{2} V_{P_0}^2$, permits it to coast the full distance, but no farther, to the point P. Suppose, secondly, that rocket B, represents the actual rocket; therefore it must leave the earth with zero initial velocity. At the distance h_p rocket B has obtained the velocity $V_P = V_{max}$ and its fuel supply has been calculated to become deleted at this point since no additional supply of energy is needed to coast the remaining distance to the objective P. Considering now the ideal rocket, rocket A, since work may be considered the product of a force and the distance over which the force is applied, the energy per unit mass required for rocket A to cover the distance h_p is

$$E_{1-2} = \int_R^{R+h_p} g \, ds$$

Although the latter equation could be integrated by combining with Equation [3], the analysis can be simplified by using a mean value of gravity $\bar{g}$ to

represent an average for the variable force of gravitation acting over the burning-time distance h_p. Then the energy per unit mass required for rocket A to cover the distance h_p is simply

$$E_{1-2} = \bar{g} h_p \quad [9]$$

Combining Equations [8] and [9] yields

$$E_{1-2} = \frac{1}{2} \bar{g} \frac{V_P^2}{g_o \nu} = \frac{1}{2} \bar{g} \frac{V_{max}^2}{g_o \nu} \quad [10]$$

The additional energy per unit mass for the ideal and actual rocket to go from position 2 to P is the kinetic energy of the rockets at position 2, which is

$$E_{2-P} = \frac{1}{2} V_{max}^2 \quad [11]$$

where V_{max} is, as before, the maximum velocity of the actual rocket. The total energy per unit mass to go from position 1 to P is simply the sum of Equations [10] and [11], that is

$$E_{1-P} = E_{1-2} + E_{2-P} = \frac{1}{2} \bar{g} \frac{V_{max}^2}{g_o \nu} + \frac{1}{2} V_{max}^2$$

$$E_{1-P} = \frac{1}{2} V_{max}^2 \left(1 + \frac{\bar{g}}{g_o} \frac{1}{\nu}\right) \quad [12]$$

For the ideal rocket, rocket A, the total energy required to go from position 1 to P, Equation [12], is obtained from the kinetic energy possessed by the rocket at 1. Hence

$$\frac{1}{2} V_{max}^2 \left(1 + \frac{\bar{g}}{g_o} \frac{1}{\nu}\right) = \frac{1}{2} V_{Po}^2$$

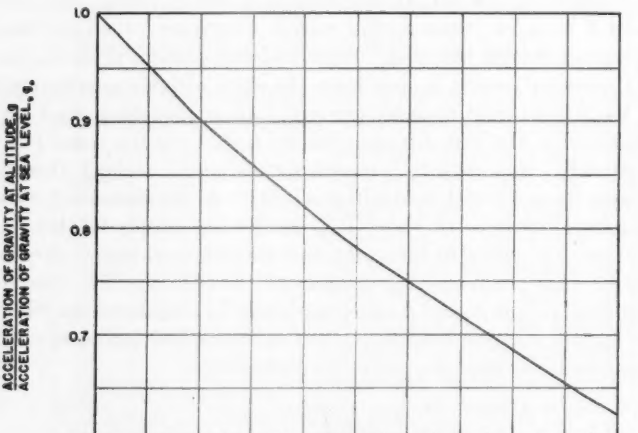


FIG. 8 RATIO OF ACCELERATION OF GRAVITY AT ALTITUDE (0–1000 MILES) TO SEA LEVEL

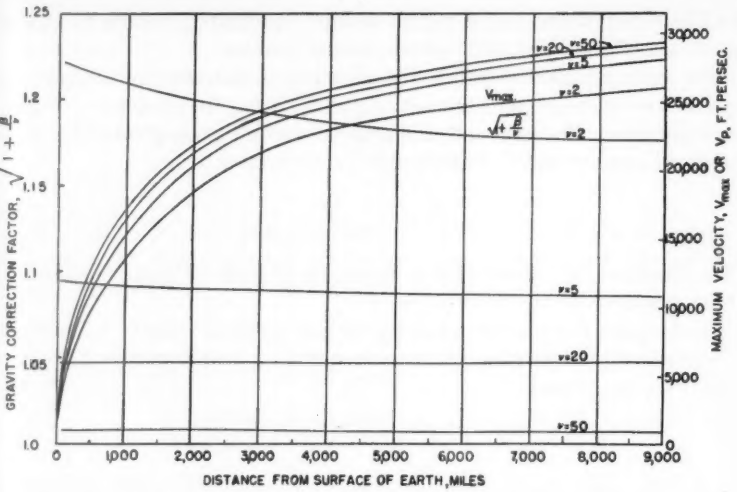


FIG 9 GRAVITY CORRECTION FACTOR AND MAXIMUM ROCKET VELOCITY AS A FUNCTION OF MAXIMUM TRAJECTORY HEIGHT FOR VARIOUS ACCELERATION PARAMETERS

Solving for V_{max}

$$V_{max} = \frac{V_{P_o}}{\sqrt{1 + (\bar{g}/g_o)(1/\nu)}}$$

For convenience let $\beta = \bar{g}/g_0$, which will be referred to as the gravity ratio. Then

$$V_{max} = \frac{V_{P_o}}{\sqrt{1 + \beta/\nu}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [13]$$

The velocity V_{max} is the required maximum velocity that the rocket must obtain to reach some point P in space. Its variation from the readily calculated velocity V_{P_o} ($V_{max} < V_{P_o}$) is given by Equation [13].

The acceleration parameter ν, of course depends to a large extent on the character of the payload and is selected by the designer of the long-range rocket after a payload consideration.

Fig. 8 shows that if h_p is equal to or less than 1000 miles a linear function may be assumed to exist between g/g_o and altitude with small error. Hence for simplicity, the gravity ratio β can be determined at the altitude $h_p/2$ if the burning time h_p is equal to or less than 1000 miles. However, since h_p is unknown along with V_P and β and only two equations are available, [8] and [13], a solution by successive approximations is necessary to determine V_{max}. Such a method was used to construct Fig. 9 which is a plot of V_{max} versus distance from the earth's surface for various values of ν.

In Fig. 9 distance from the earth's surface represents of course the maximum height of the vertical trajectory rocket in miles.

For meteorological rockets designed to reach relatively low altitudes, of say, 750 miles or less, the variation of gravity during the accelerated or powered portion of the flight will be negligible, and the gravity ratio β may be assumed equal to unity. Equation [13] then reduces to

$$V_{max} = \frac{V_{P_o}}{\sqrt{1 + 1/\nu}} \quad [14]$$

The German V-2 rocket with a maximum altitude of approximately 114 miles comes under the latter category.

If the point P is moved to infinity the gravitational velocity V_{P_o} becomes the sea-level velocity of escape from the earth V_{e_o}, and Equation [13] can be rewritten as follows

$$V_{max} = V_s = \frac{V_{e_o}}{\sqrt{1 + \beta/\nu}} = \frac{36{,}700}{\sqrt{1 + \beta/\nu}} \quad [15]$$

For the particular problem of escape from the earth, unlike the general case of the flight to a point P, three equations are available, [6], [8], and [15], with three unknowns h_p, β, and V_c, and the value of the gravity ratio β corresponding to a particular acceleration factor ν can be easily calculated.[3] Table 1 lists the values of β for several values of ν. The values of β given in Table 1 of course apply only to the escape mission.

Over-All Mass-Ratio

In the preceding section equations were derived which permitted the calculation of the theoretical maximum velocity that the long-range and escape rocket must be capable of obtaining in order for the rocket to achieve a given altitude or to escape from the earth with the minimum expenditure of energy.

Of utmost practical interest to the rocket designer and to the agency supplying the financial backing for long-range rocket flights is information pertaining to the over-all size of the rocket and the total quantity of fuel that will be required for a given mission.

In this section of the paper the maximum velocity requirement of the preceding section will be used to determine the minimum gross initial mass of a rocket M_o required to transport a given mass M, which

TABLE 1 GRAVITY RATIO β FOR VARIOUS VALUES OF THE ACCELERATION PARAMETER ν APPLICABLE TO THE ESCAPE MISSION

$\nu = \frac{\bar{a}}{g_o}$	$\beta = \frac{\bar{g}}{g_o}$
1	0.61
5	0.84
10	0.88
20	0.96
∞	1.00

[3] Note that $V_s = V_{max}$ and $s = h_p$ in the solution of Equations [6], [8], and [15].

includes the mass of the empty[4] rocket and the mass of the payload, to a desired height P or to escape from the earth. The ratio M_o/M, following conventional notation, will be designated as the over-all mass-ratio of the rocket.

The thrust of a rocket motor is given (9) by the momentum equation

$$F = \frac{G}{g} c \quad \text{[16]}$$

where c is the effective exhaust velocity of the gaseous products of combustion and G/g is the mass rate of flow of these gases through the exhaust nozzle. Hence

$$\frac{G}{g} = \frac{dm}{dt} \quad \text{[17]}$$

Comparing Equations [16] and [17] gives

$$F = -\frac{dm}{dt} c \quad \text{[18]}$$

The minus sign is necessary since the propellant mass is decreasing with respect to the rocket system with time, that is, the gaseous products of combustion are expanded and discharged through the rocket nozzle. The external forces acting on the rocket while in vertical flight neglecting the resistance of the atmosphere and the earth's rotation, are the thrust from the rocket motor F and the attraction of the earth's gravitation. (See Fig. 1.) From Newton's Law, $F = ma$, the relationship between the external forces and the acceleration of the rocket is

$$F - mg = ma = m\frac{dv}{dt} \quad \text{[19]}$$

Rearranging Equation [19] and combining with Equation [18] yields

$$dv = -c\frac{dm}{m} - g\,dt \quad \text{[19a]}$$

The rocket will obtain its maximum velocity at the end of powered flight when the propellants have been consumed. The integration limits for V_{max} are then

$$v = o \text{ and } m = M_o \text{ when } t = o$$

$$v = V_{max} \text{ and } m = M_o - M_p \text{ when } t = t_p$$

Substituting the above limits of integration into Equation [19a] yields

$$\int_o^{V_{max}} dv = -\int_{M_o}^{M_o - M_p} c\frac{dm}{m} - \int_o^{t_p} g\,dt$$

Using a time average value of the effective exhaust velocity, $\bar{c}$, and integrating

[4] The adjective "empty" refers to the rocket after the propellants have been consumed.

$$V_{max} = \bar{c} \log_e \left(\frac{M_o}{M_o - M_p} \right) - \int_o^{t_p} g \, dt$$

But by definition

$$M_o = M + M_p$$

so

$$V_{max} = \bar{c} \log_e \frac{M_o}{M} - \int^{t_p} g \, dt \quad \text{[20]}$$

The integral $\int_o^{t_p} g \, dt$ represents the decrease of the maximum velocity of the rocket with a given c and M_o/M due to the attraction of the earth. Unfortunately, it cannot be integrated without additional design and trajectory information. However, as was done in the derivation of Equations [13] and [15], a mean value of gravitation $\bar{g}$ can be used for over the burning period of the rocket. Thus Equation [20] becomes

$$V_{max} = \bar{c} \log_e \frac{M_o}{M} - \bar{g} t_p$$

Eliminating t_p by combining the latter equation with Equation [8] yields

$$V_{max} = \bar{c} \log_e \frac{M_o}{M} - \bar{g} \frac{V_{max}}{g_o \nu} = \bar{c} \log_e \frac{M_o}{M} - \frac{\beta}{\nu} V_{max}$$

Substituting for V_{max} Equation [13] gives

$$\frac{V_{Po}}{\sqrt{1 + \beta/\nu}} = \bar{c} \log_e \frac{M_o}{M} - \frac{\beta}{\nu} \frac{V_{Po}}{\sqrt{1 + \beta/\nu}}$$

$$V_{P_o} = \bar{c} \frac{1}{\sqrt{1 + \beta/\nu}} \log_e \frac{M_o}{M}$$

or

$$\frac{M_o}{M} = e^{(V_{P_o}/\bar{c})\sqrt{1 + \beta/\nu}} \quad \text{[21]}$$

For rockets designed to reach relatively low altitudes, of, say, 750 miles or less, the variation of gravity during powered flight is negligible, that is, $\beta \backsimeq 1$, and the over-all mass-ratio equation is

$$\frac{M_o}{M} = e^{(V_{P_o}/\bar{c})\sqrt{1 + 1/\nu}} \quad \text{[22]}$$

For rockets designed to escape from the earth Equation [15] is used above in place of Equation [13] giving

$$\frac{M_o}{M} = e^{(V_{e_o}/\bar{c})\sqrt{1 + \beta/\nu}} = e^{(36{,}700/\bar{c})\sqrt{1 + \beta/\nu}} \quad \text{[23]}$$

The significance of the gravitational velocities V_{P_o} and V_{e_o}, the acceleration factor ν, and the gravity ratio β have been discussed in some detail.

Although a good understanding of the effective exhaust velocity c cannot be had without recourse to a study of the internal ballistics of the rocket motor (9), an inadequate explanation of c may be justified here in order to clarify its use in Equations [21], [22], and [23]. The effective exhaust velocity is essentially a function of the following:

1 Rocket-propellant combination
2 Rocket-nozzle expansion ratio and rocket-motor design
3 Atmospheric pressure surrounding the exhaust nozzle.

Since these three factors can be controlled accurately or measured in static rocket tests, the effective exhaust velocity is a useful rocket parameter, especially for comparing rocket propellants. Due to the dependence of the effective exhaust velocity upon the atmospheric pressure surrounding the outlet of the nozzle, the effective exhaust velocity increases as the vertical trajectory rocket gains altitude and encounters less dense air. This increase was conveniently taken care of above by using a time-average value of the effective exhaust velocity $\bar{c}$ in the derivations of Equations [21], [22], and [23].

Since Equation [22] has a minimum value

$$\left(\frac{M_o}{M}\right)_{min} = e^{\sqrt{p_o}/\bar{c}}$$

when $\nu = \infty$, that is, instantaneous burning, the exponential factor of Equation [22], $\sqrt{1 + \beta/\nu}$, may be considered the gravitational correction factor made necessary due to the actual rocket having a finite burning period. The numerical magnitude of the correction factor can be obtained from Fig. 9 for heights up to 9000 miles. The pertinent question as to whether it is necessary to consider the variation of gravitation during powered flight is an individual problem since the answer depends on the acceleration parameters being considered and the degree of accuracy desired in the calculations. In any case Fig. 9 can be used to calculate quickly the error introduced by assuming $\sqrt{1 + \beta/\nu} = 1$, and also may be of some academic interest.

Examples

A better understanding of the theoretical review and analysis can perhaps best be obtained by following through some simple numerical examples.

Example 1. It is desired to compare the calculated mass-ratio value from Equation [22] with published data (3) of the German V-2 rocket.

Maximum height	114 miles
Average effective exhaust velocity, $\bar{c}$ (approx.)	7380 fps
Average acceleration during powered flight	$2g_o$
Mass ratio M_o/M	2.75

Using the above information and Equation [22], calculate the ratio of the initial mass of the rocket M_o to the mass after the propellants have been consumed, M, and then compare the theoretical value to the supposedly actual value of 2.75.

Solution. From Fig. 5 the gravitational velocity corresponding to the V-2 maximum height of 114 miles is 6385 fps. Substituting this value and V-2 data from above into Equation [22]

$$\frac{M_o}{M} = e^{(V_{P_o}/\bar{c})\sqrt{1 + 1/\nu}} = e^{(6,385/7,380)\sqrt{1 + 1/2}} = 2.88$$

The above theoretical mass-ratio value compares closely with the published 2.75 V-2 mass ratio.

Example 2. A vertical trajectory rocket is to be designed to reach an altitude of 1000 miles. It is to have the following characteristics:

$$\bar{c} = 11,000 \text{ ft per sec}$$
$$\nu = 5$$

Determine: 1, The maximum velocity of the rocket V_{max}; 2, the distance covered during powered flight h_p; and 3, the over-all mass-ratio M_o/M of the rocket. Compare 3 with the mass ratio of the ideal rocket, $(M_o/M)_{min}$.

Solution. From Fig. 9, for $\nu = 5$ and a distance of 1000 miles from the earth's surface

$$V_{max} = 15,100 \text{ ft/sec}$$

From Eq. [8]

$$h_p = \frac{15,100^2}{2 \times 32.2 \times 5 \times 5280} = 134.12 \text{ miles}$$

From Fig. 9

$$\sqrt{1 + \beta/\nu} = 1.093$$

From Fig. 5

$$V_{P_o} = 16,480 \, fps$$

From Eq. [21]

$$\frac{M_o}{M} = e^{(16,480/11,000)\ \ 1.093} = 5.14$$

For the ideal rocket

$$\left(\frac{M_o}{M}\right)_{min} = e^{(16,480/11,000)} = 4.48$$

Per cent deviation between ideal and actual = 13

Example 3. It is desired to calculate the mass ratio M_o/M of a single-step rocket designed to escape from the earth. The rocket propellants are

to be liquid hydrogen and liquid oxygen. The combustion-chamber pressure is to be 300 psia and the area ratio, exit area to throat area of the nozzle, is to be 25:1. The rocket is to be designed for an average acceleration of 5 g_o during powered flight.

Solution. Equation [23] is applicable. The maximum sea-level effective exhaust velocity obtainable from liquid oxygen and hydrogen for an expansion of 300 psia to one atmosphere is about 10,150 fps. The time average effective exhaust velocity $\bar{c}$ over powered flight will be somewhat larger due to the decreased atmospheric pressure at altitude. Therefore the value, 10,150 fps, must be corrected by a factor greater than unity before it can be substituted in Equation [23]. The magnitude of the correction factor will depend on the nozzle expansion ratio and the average acceleration during powered flight. For a 25:1 expansion ratio and a 5 g_o rocket it can be shown (10) that $\bar{c}$ will be approximately 1.22 times the maximum sea-level value. Hence

$$\bar{c} = 10{,}150 \times 1.22 = 12{,}383 \text{ fps}$$

From Table 1 the gravity ratio β corresponding to $\nu = 5$ is 0.84.

Substituting into Equation [23] gives

$$\frac{M_o}{M} = e^{(36{,}700/12{,}383)\sqrt{1 + (0.84/5)}} = 24.53$$

It can easily be shown that a single-step rocket with such a high mass ratio is not likely to be built. Since by definition

$$M_p + M = M_o$$

then

$$\frac{M_p}{M_o} + \frac{M}{M_o} = 1$$

Assume $M/M_o = 24.53$ as calculated above, then

$$\frac{M_p}{M_o} = 0.959$$

The construction of a liquid-hydrogen and liquid-oxygen rocket which is 95.9 per cent propellants appears at this time improbable.

References

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ARS Activities

ARS 1948 National Convention

THE THIRD National Convention of the American Rocket Society will be held in co-operation with The American Society of Mechanical Engineers, Thursday, Dec. 2, 1948, at the Hotel Pennsylvania, New York, N. Y. The program follows:

THURSDAY, DECEMBER 2

9:30 a.m.

Chairman: Morton Gerla, vice-president, Superior Development Corporation, consulting engineers, New York, N. Y.

Recorder: Bernard Fishman, project engineer, M. W. Kellogg Company, Jersey City, N. J.

A Study of the Parameters Affecting Overall Rocket Performance, by Charles H. Harry, pilotless aircraft section, Glenn Martin Company, Baltimore, Md.

A Survey of Injector Designs for Use in Liquid Propellant Rocket Motors, by B. M. Abramson, Bell Aircraft Corporation, Buffalo, N. Y.

12:15 p.m.

LUNCHEON

Presiding: Charles A. Villiers, president, American Rocket Society.

Subject: The Muroc Facility

Speaker: K. F. Mundt, chief engineer, Aerojet Engineering Corporation, Azusa, Calif.

2:30 p.m.

Chairman: James Wheeler, Sperry Gyroscope Company, Great Neck, L. I., N. Y.

Recorder: Leonard Axelrod, project engineer, M. W. Kellogg Company, Jersey City, N. J.

Creation of High Pressure Gas Source for Rocket Motor Propellant Supply Systems, by C. J. Turansky and R. D. Rinehart, rocket group engineers, Bell Aircraft Corporation, Buffalo, N. Y.

Metal Parts for Solid Propellant Rockets, by L. G. Bonner, technical director, Allegany Ballistics Laboratory, Cumberland, Md.

6:00 p.m.

DINNER

Toastmaster: G. Edward Pendray, Pendray and Liebert, New York, N. Y.

Subject: Rockets as Research Tools in Aeronautics.

Speaker: Hugh L. Dryden, director of aeronautical research, National Advisory Committee for Aeronautics, Washington, D. C.

Awards: R. H. Goddard Memorial Lecture Awards, to John Shesta, Reaction Motors, Inc.

C. N. Hickman Award, to Frank Malina, UNESCO.

American Rocket Society Junior Award, recipient to be announced.

Comments

Vulnerability

To the Editor:

WITH our country spending hundreds of millions of dollars on new turbojet engines for military aircraft, I wonder if thorough consideration has been given to the apparent vulnerability of these engines as now built?

It appears that the air suction is strong enough to pick up small pieces of metal which could cause the rotors, particularly of axial-flow compressors, to explode and destroy the entire ship. It is known that a man can be sucked into the air scoop of a jet plane if he gets within two or three feet of it. With the compressor rotor blades turning at 9000 rpm and up, this means that any debris in the path of the plane, such as shrapnel particles, large buckshot sent up by antiaircraft batteries, etc., could cause the rotor blades to break, unbalance the rotor, and destroy the plane, if the engine is mounted within the plane. There would be no need of attempting to aim at an attacking formation of jet planes if merely shooting hard pellets vertically into their path would make them destroy themselves.

On the other hand, where screens are used between the scoop and compressor, perhaps effective antiaircraft would consist of filling the air with say 6-in. squares of plastic membranes which on being sucked in over the air intake screens would shut down on the air supply and cause the turbojets to burn up or otherwise fail.

These turbojets have not had extensive battle testing and before we trust our air security too completely to this type of engine I hope a complete answer is engineered to overcome this vulnerability. It is interesting to note that the Russian four-jet Ilyushin bomber hangs its turbojets on long struts below the wings which would allow arming the bottom of the wing and the side of the fuselage.

An article by George Carroll in one of the New York newspapers is pertinent; "LeVier had a turbine wheel fail at 540 mph. This cut off the whole aft end of the airplane. While the pilot escaped safely, the wheel was not found for a year, even after a most extensive and highly scientific search," recounted Johnson. This shows the terrible forces let loose if a high-speed wheel is unbalanced or breaks inside a plane. Less ram effect and less speed with more safety, may be the solution.

WADSWORTH W. MOUNT[1]

[1] Mem. ARS, Engineering Consultant, Summit, N. J.

Science Fiction

To the Editor:

I wish to compliment Maj. Randolph on the June, 1948, issue of the JOURNAL as it was very nicely done.

I should also like to enter the Science Fiction controversy by pointing out that the main thing wrong with Science Fiction today is the fact that the editors write most of the stories. If this is not a sure formula for decadence in literature I should like to know how much worse the situation could get. When you realize that the leading monthly Science Fiction magazine comes out twelve times a year, and averages 4½ stories per issue, with perhaps one half of them written by the editor and the rest by the leading "names," it becomes apparent why they fall into ruts; or shall we say, "vortexes in hyper-spacebunk"?

R. L. FARNSWORTH[1]

[1] President, United States Rocket Society, Glenn Ellyn, Ill.

Arctic Air Aids

A CHAIN of long-range navigation stations stretching across the arctic frontier of Alaska and Canada is nearing completion. The stations will be of inestimable value to air navigators flying to the North Pole and across any part of the polar ice packs, permitting the navigators to fix the position of plane exactly when no other means of navigation is available.

LEADER *in the field of Research and Development of Solid Propellant and Liquid Propellant* Rocket Power Plants

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